JRC TECHNICAL REPORTS

Revision of Green Public Procurement Criteria for Road construction

Supporting documents of the Preliminary report

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Some sections of this document are adapted from a preliminary contribution sent by COWI A/S.

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ANNEX I. SCOPE DEFINITION, LEGISLATION, EXISTING GPP CRITERIA, LABELS AND STANDARDS

I.1 Stakeholders feedback on scope and definition

In the questionnaire sent to the stakeholders on March 2013, this scope and definition have been proposed:

At first, the scope of the different elements to be addressed with these GPP criteria must be identified and robust definitions must be found.

The definition for the previous Green Public Procurement (GPP) specifications is:

- Road construction: "*the preparation and building of a road using materials including aggregate, bituminous binders and additives that are used for the sub-base, road-base and surfacing layers of the road*"

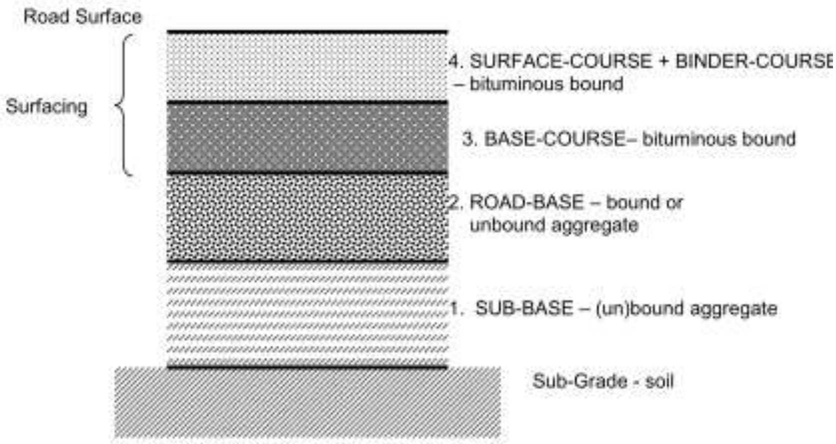

Figure I.1: Diagram illustrating the flexible pavement system

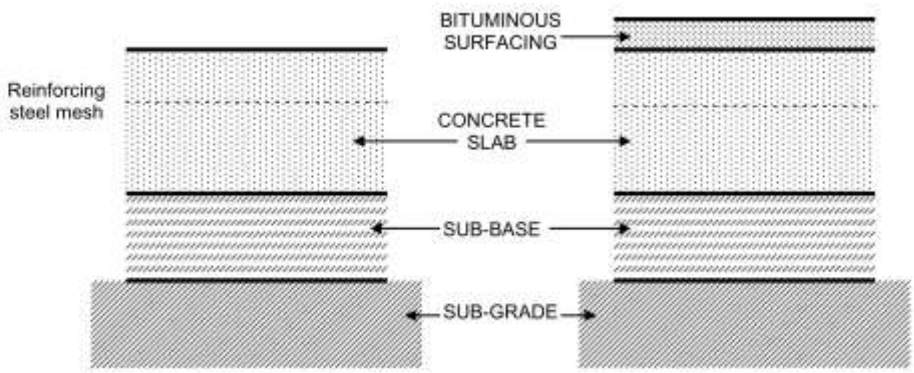

Figure I.2: Diagram illustrating the rigid pavement layer system

It is proposed to keep the definitions above from the previous Green Public Procurement criteria for Road Construction and traffic signs.

Stakeholders feedbacks are reported below.

Table I.1: Stakeholder feedback and suggestion regarding definitions

Given the proposed scope and definition, considering the definition title e ”Road pavement construction”. Even here however, if full life cycle is being addressed, then the term ”construction” could be interpreted as excluding ”maintenance and operation (road user)”. Has simply ”Road pavement” been considered?
Under a rigid pavement there is also a sub grade-soil. Groundworks in preparations is a major environmental issue; please make sure to include this in the analyses
The definition above is in conflict with Annex I where you suggest including a hydraulically bound base course
Please consider adding also geotextiles and geosynthetic barriers for road construction into the scope.
Composite pavement layer systems (as mentioned in the annex) also remain possible (in particular for renovation). In these cases a layer that prevents cracking can be added between the base course (hydraulically bound) and the surface course. Depending on the type of base course this layer can consist of a bitumininous product, eventually completed by a reinforcing mesh.
It is recommended that for white-topping should also be included an alternative method within the definition of a flexible payment whereby the surface course is a concrete layer is laid over a flexible base course. Expoxy-based surfacing could be considered as well as the possible inclusion of patching materials eg pothole repair. It is assumed that construction and reconstruction of roads (and harbours/ports) with traditional elements, eg cobbles and block paving, would in most cases be outside of the scope It is not clear how prefabricated road elements would fit within this definition whereas novel surfacing. Moreover the use of ’novel’ materials such as photovoltaic panels in/as the surface could be considered
Cement is a hydraulic binder, not an additive; so it is better to talk about ”bituminous and hydraulic binders”. In a complete concept of a rigid pavement structure, a road-base is also to be considered. In addition, very often a sandwich layer is placed between the road-base and the concrete slab. This sandwich layer mostly is a bituminous layer, sometimes a geotextile. The reinforcing steel mesh is not a standard option. In most cases, for jointed plain concrete pavements (JPCP), the concrete is not reinforced. In case of continuously reinforced concrete pavements (CRCP), usually not a steel mesh is used but separate longitudinal steel bars (mostly place upon transverse steel bars).

Table I.2 Stakeholder feedback and suggestion regarding scope

Agreement on the scope		
Yes	No	If no, what is your suggestion regarding the scope
		The scope as it stands is potentially very narrow in looking to influence mainly ‘civils/pavement’ type works, and therefore ignores a considerable fraction of roads investment at this time. The analysis used by Stripple is a simple emissions inventory which has excluded more complex environmental effects and is therefore skewed largely by embodied energy considerations – resulting in a relatively inflexible framework. The exclusion of fencing for this reason is puzzling given that it features in the generic construction GPP, and would be easily transposed.
		GPP is for procurers, so the scope should be defined by the content of actual contracts and not by technical components. E.g. In procurement other elements can be easily included, such as criteria on the obstruction of traffic (high indirect CO2 effects) during constructions works. These are not mentioned yet. And if you refer to other documents for e.g. street lighting or traffic signs; these documents should be analysed in coherence and overlap should be checked carefully included; e.g. the reflection of the pavement, traffic signs and street light are linked. So Yes, only if the development of the analyses and criteria are based on whole scope of the road and environment including options for a performance based approach. We suggest to include ground works (which is not clear to us now), traffic management during the construction works and the use of performance based instruments for the whole construction. Also we suggest to include airfields, because they are constructed in the same way as roads.
		Noise is a very important impact issue for roads. Including an impact category on noise (as the one recently developed within the EU project LC-Impact) in LCA’s on roads will probably show that this type of impact becomes significant for the LCA impact profile. Including one type of noise barrier (earth mounds) but excluding all others seems strange. I suggest that you include noise barriers
		Agreement to all listed points, but suggest to add geotextiles and geosynthetic barriers as already mentioned in the answer to question 1.
		Should vehicle restraint systems. Different solutions exist (precast concrete, steel, wood, in situ cast concrete) which all have a different environmental impact during the phases that are considered
		The inclusion of some additional elements has merit. For example, it is recognised that much of the

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<tr><td></td><td></td><td>environmentally toxic effects of roads are related to accidents during their operation phase. Pollution of water courses from run-off has been found (WATMOVE project) to be a predominately caused by accidents involving vehicles. Therefore drainage has a role to play in pollution control as well as in water course management (eg flood control).
The definitions for the exclusions could be considered too broad and imprecise. There is some concern that unclear definitions will leave some elements excluded under the GPP.
For example, not all road markings in the future will be ‘paint’. LED based systems are under development and be used in some case. Trials in Norway have also considered the use of lasers in tunnels and these might be used more widely. Such ‘lighting enhanced’ road markings would appear to be outside of the scope of the GPP criteria on street lighting.
The criteria for noise barriers suggest a large grey area. If the intention is for barriers predominantly constructed of metal or wood - or perhaps glass or similar - this is understandable, but barriers largely constructed of concrete or earthworks for acoustic purposes that contain geotextiles, polystyrene, scrapped tyres etc might be better to included.

Note also that foundations for lighting and gantries can be included as part of road construction when integrated into, for example, concrete barriers in the central reservation. Also some metallic safety fences have been implicated in studies of roadside pollution related to their corrosion (ref?)
Note also that several of the excluded components can indirectly influence the road vehicle energy consumption (e.g. road markings, traffic signs, information systems).</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Road furniture should be included in the scope (at least c) d) e) f) as described on previous page). The reason is the following:
1. GPP and more in general sustainable public procurement is an aspirational target and any possible means to support this effort should be taken into consideration not just in terms of what they represent in terms of percentage of the total potential environmental impacts but more broadly in terms of benefits they bring to the society, the environment and the economy. If one should take into consideration only the criteria of percentage of the total environmental impacts to define the boundaries of the system and consequential necessity for action, then one should wonder why bothering with road infrastructure which represents – according to several studies – only 2 - 4% ot the toal emissions produced by the road transport sector.
2. Like it has happened with eco-labels or other GPP criteria (outside the road sector) some categories of products offer easy “quick wins” meaning criteria for these products can be easely developed and applied thus contributing to creating a positive culture around the whole idea of GPP and a number of “success stories which will benefit the entire programme, particularly in areas (like road sector) that are a bit more problematic.The inclusion of road furniture would in fact serve this purpose. This will help creating that change in mindset which is required to succeed with this initiative.
3. It offers an excellent opportunity to spur innovation often at no extra cost.
These points are supported by several documents produced by the European Commisison itself:
“The idea of shifting to sustainable consumption and production represents a difficult challenge within a single country and at global level, but also an opportunity for economic and competitive development. A more efficient use of resources offers benefits to society, the environment and the economy.
Sustainable consumption and production is a fundamental target to get a sustainable development of the European Union. This is the overarching long term goal of the European Union set out in the EU Treaty in Maastricht in 19921. It calls for the inclusion of sustainability considerations and targets into all European policies, so that they can contribute in an integrated way to meeting economic, environmental and social objectives. Changing the consumption patterns of private and public purchasers can help drive resource efficiency and frequently generates direct net cost savings as well. In turn, it can support increase demand for more resource efficient services and products. Accurate information, based on the life-cycle impacts and costs of resource use, is needed to guide consumption decisions and allow consumers to save costs by avoiding waste as well as buying products that can be easily repaired or recycled.
Using resources more efficiently, in particular, will help to achieve many of the EU’s objectives. It will be a key in making progress to deal with climate change and in achieving the EU's target of reducing EU greenhouse gas emissions by 80 to 95% by 2050.” [Background document to the stakeholder consultation on sustainable production and consumption (2012), p. 3].
More over, in the document distributed together with this questionnaire, it is stated:
“Several studies indicate that there is a clear connection between durability and sustainability aspects including environmental impacts. Thus when durable materials are used the need for maintenance is reduced.”</td></tr>
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		"*One of the priorities in implementing a SCP set of actions that contribute to the Resource Efficiency Agenda is* ***to stimulate producers to supply products the design and production processes of which are based on resource efficiency and life-cycle considerations, as part of an extended producers responsibility approach.*** *This goal can be achieved through a consistent mixture of regulatory and voluntary measures in order to boost environmental performance. Such measures can include actions for strengthening the effectiveness of the existing EU SCP regulatory instruments and policy measures and the setting up of new instruments and standards. Particularly****, actions can be envisaged to increase the opportunities for producers to gain a competitive advantage on the market as a reward (and a stimulus) for the production of more sustainable products***." [Background document to the stakeholder consultation on sustainable production and consumption (2012), p. 6].
		I don't see the reason why road markings and road signs (even more road signs as they are incorporated in the title GPP criteria for road construction and traffic signs). Regarding road markings, the EU Ecolabel documents only refer to the composition/components of the materials in the classification of 'outdoor paints'. According to this proposal (1. Background and particularly point 1.3) the 'use phase' appears to be the most important one as it is contributing to the largest potential environmental impacts caused by traffic. If we consider this particular phase which can extend up to 50 years, this is the time when many operations of maintenance of the traffic signs and road markings will take place. Better performing materials and systems will reduce the number of maintenance and repair operations, thus contributing a lot to the reduction of congestion, emissions, bottlenecks… which will have a great influence on the environmental final impact.
		Road furniture does impart some quick opportunities ("low hanging fruit"). This may be beneficial for the overall success of the program as the "road construction and maintenance" looks like a big opportunity, defining and enforcing success will be quite a challenge… Concrete vs Asphalt?
		It seems better to keep it restricted to the road itself without drainage system and earth mounds. It is not clear where the drainage systems stops (if there is a sewerage system under or next to the road, should it be included or not; if yes, you are in a comparison of other materials and applications). It should be better specified if all earthworks need to be included. How to compare the performance of an earth wall, serving as noise barrier with standardized, tested and CE-certified "Road traffic noise reducing devices" ?
		There are two key phases of the life cycle that are not included in the scope phases identified: 1. Transportation of the raw materials/ready to use products from the extraction/processing site to the job site. Depending on the transportation distances (5 or 50, or 100 km) the impacts will be different; 2. Recycling phase. During the maintenance, there is a part of the asphalt that is reused, therefore meaning less primary resources needed and as a result a smaller environmental impact is expected. The re-road project have a lot of information on the recycling (in situ or Plant mixed recycling) which is important to be taken into account in the scope analysis. Comments on raw materials extraction The raw material is it referring to extraction? Therefore EuLA would suggest to add the word "extraction" for clarity as well as to clarify what is in the scope. Additional steps which can be added are also pre-processing (grinding)? Final processing (which improves functionality)? Please clarify whether this steps are needed for quantification of the impacts within a LCA approach.
		There are significant differences in the quantity of materials need for crash barriers and the central reservations, and so these should be included in the scope. A concrete central reservation uses much more material than a steel barrier system, which can mean significant differences in environmental impact, notwithstanding any additional differences in foundation or drainage design. This difference could influence the choice of materials used, and so it should be in the scope of the assessment otherwise it will not be quantified.

I.2 Additional information on the Directives on Public procurement

Contractual terms
As regards contractual terms, there may be a number of points that are fixed in the draft contract which is part of the tender dossier issued by the procuring authority. This would include classical terms concerning liability, compensation etc., and any alternative proposals or reservations on the part of a tenderer will in many cases result in the bid being rejected as non-responsive along the same lines as in the case of technical specifications. Contractual terms of environmental relevance include for example requirement for insurance to cover any environmental liability or obligations. The operator could also be put under a contractual obligation to regularly report on environmental matters to the procuring entity to enable fulfilment of information obligations in relation to the public.

Selection criteria
Selection or qualification criteria determine which operators are eligible to submit a tender. These may either be assessed as part of a two-stage procedure (e.g. the restricted procedure) where a shortlist of tenderers is drawn up, or in an open procedure they act as threshold conditions determining which tenders go through to full evaluation. The directives set out an exhaustive list of the matters which can be examined at selection stage and the evidence which may be required. This means that other matters cannot be used as the basis for excluding operators from the competition. Under the directives selection criteria must concern the financial and economic standing or technical and professional capacity of operators. Furthermore they must be allowed to rely on the capacity of other organisations (e.g. subcontractors or partners in a consortium) in order to meet the criteria. Selection criteria of environmental relevance would for example concern specific environmental management experience and qualifications of staff.

Technical specifications
Technical specifications define the characteristics of the good, service or works being procured and are mandatory requirements which a tender must meet. If tenderers deviate from the specifications in their bids, the effect is that the bid must be rejected as non-responsive. Submission of alternative solutions may be authorised in the form of variants, however the contracting authority must still specify its minimum requirements. Technical specifications can be a very effective way of communicating environmental priorities, as all bids will need to meet the requirements in order to be considered for contract award.

In the context of road construction, typical specifications to safeguard environmental concerns would include the use of certain eco-friendly materials, requirements for the capacities and efficiency of the infrastructure, requirements regarding the rolling resistance, and other control procedures and requirements regarding the energy-efficiency and waste management levels of the operation in general. In the case of project–oriented procurement involving design, construction and operation, the technical specifications concerning the construction may be output-based or functional, leaving it open for each tenderer to design his own technical approach. This allows tenderers to choose (and take the risk for) solutions fulfilling the output requirements (including environmental ones) which best suit their operations.

Award criteria
Award criteria provide the basis for evaluating tenders and for identifying the winning bid. This phase of the procurement process involves bids from tenderers that have been evaluated as qualified and whose bids are otherwise compliant with technical specifications as well as the contract terms. The award criteria define the themes for competition, and the directives allow a choice between either lowest price only or the most economically advantageous tender (MEAT). It is in the latter case that environmental aspects become relevant. Use of MEAT allows costs to be assessed on the basis of LCC, either on a purely financial basis or with the inclusion of monetised environmental externalities.

The award criteria must relate to the bid and must not be confused with the above qualification criteria, which concern the evaluation of the tenderers' ability to perform the contract in question. Award criteria can on the other hand include issues that might as well have been used as technical specifications or for that matter contract terms. Award criteria may be formulated as performance requirements where tenderers are invited to commit to higher levels of (for example) reduced energy consumption during the use phase, minimum maintenance etc. Award criteria could allow tenderers to propose terms that go beyond a minimum that the contract prescribes, for example higher levels of investment or higher/stricter targets for pollution control on site, including reduction of other effects, such as noise.

I.3 Sustainable Public Procurements

The Marrakech Task Force on Sustainable Public Procurement (MTF on SPP) led by Switzerland from 2006 to May 2011 has developed an approach for implementing sustainable public procurement (SPP) in both developed and developing countries, known as the MTF Approach to SPP.

In 2008, the Swiss government and the United Nations Environment Programme (UNEP) designed a project to roll out this approach in 14 countries worldwide. This project, entitled Capacity building for Sustainable Public Procurement in Developing Countries, is supported by the European Commission, Switzerland and the Organization of Francophone countries. It is currently being implemented by UNEP and piloted in Chile, Colombia, Costa Rica, Lebanon, Mauritius, Tunisia and Uruguay. The Marrakech Task Force approach to sustainable public procurement

The approach applies as follows: first, pilot countries assess their procurement status through an online questionnaire. Second, a review is undertaken to identify the legislative framework for procurement in the country and to analyse the possibilities for integrating social and environmental criteria into procurement activities. Third, a country-based market readiness analysis is carried out in order to define the existing productive capacities for sustainable products and services and the potential responsiveness of the market to SPP tenders.

After successful completion of these three actions, pilot countries develop a country-based SPP policy and Action plan, including a capacity building programme for procurement officers. Experts from UNEP as well as the Marrakech Task Force will assist the pilot country in the implementation of its SPP policy during one year.

The main objective of the project is to support the development and the implementation of national

SPP policies in a number of pilot countries through the testing of the MTF approach on SPP.

The ultimate goal is to assist developing countries in addressing environmental, economic and social issues through their procurement activity. A number of capacity building activities have taken place to enable public procurers and policy makers to implement sustainable public procurement. UNEP also assists its local partners in identifying the social, environmental and economic benefits of buying more sustainably (e.g. reduced ecological footprint, enhanced innovation and competitiveness as well as an increased availability of sustainable products and services, etc.).

The lessons learned from the project will help to improve the approach and will result in a standard methodology for the development and implementation of a national policy on sustainable

The SPP Approach guides countries through a set of steps in building an effective SPP programme. The goal is to create a policy framework that legitimizes the SPP actions and, in turn, informs the market of the objectives and priority areas so that it can gradually adapt. The SPP Approach is conceived as a series of stages or steps that must be followed to first design, then implement, a policy and action plan. The SPP Approach encourages public authorities to move towards more sustainable public procurement in a systematic and consistent manner.

The SPP Approach is structured into the following four key steps:

• Step 1: Launch the project, establish project governance and conduct initial training;

• Step 2: Undertake a Status Assessment; Legal Review, Prioritisation Exercise and Market Readiness Analysis;

• Step 3: Do Strategic Planning, create a SPP Policy and Action Plan; and

• Step 4: Implement SPP throughout the procurement cycle.

I.4 Additional information on other rating systems

CEEQUAL rating system

CEEQUAL, originally called the '**C**ivil **E**ngineering **E**nvironmental **Qual**ity Assessment and Awards Scheme' is the Assessment and Awards Scheme for improving sustainability in civil engineering, infrastructure, landscaping and public realm projects, based in the United Kingdom. It is promoted by the Institution of Civil Engineers (ICE) and several civil engineering organisations including CIRIA, CECA and ACE. It is aimed at improving the environmental and social performance in project specification, design and construction.

Through the development of Version 5 of the Methodology, original CEQUAL has turned into the 'Sustainability Assessment and Awards for Civil Engineering, Infrastructure Landscaping and Public Realm Works'. Being evidence-based, it provides a sustainability rating system for project and contract teams. Using extensive industry experience, the Scheme has been weighted to reflect both the contribution of performance in each section of a CEEQUAL Assessment to overall performance, and weighted to reflect the relative importance of the questions within their section.

CEEQUAL rewards project and contract teams in which clients, designers and contractors go beyond the legal, environmental and social minima to achieve distinctive environmental and social performance in their work.

CEEQUAL is available in three forms:

- CEEQUAL for UK & Ireland Projects
- CEEQUAL for International Projects
- CEEQUAL for Term Contracts.

A CEEQUAL score indicates how far a project is between minimum legal compliance and pinnacle best practice.

The Award thresholds, based on the maximum possible score for the project or contract, are:

- more than 25% - Pass
- more than 40% - Good
- more than 60% - Very Good
- more than 75% - Excellent.

CEEQUAL FOR PROJECTS

The CEEQUAL Project Assessment process is applicable to all types of civil engineering, infrastructure, landscaping and public realm projects, including the infrastructure associated with building developments, whether the project is located in the UK & Ireland or anywhere else in the world.

For Projects, five types of Award are available:

- Whole Project Award (WPA) – the normal Award, applied for jointly by the client, designer and principal contractor(s)
- Client & Design Award – for a joint application by the client and designer
- Design Award – only for principal designers
- Design & Build Award – for a joint application by the contractor and the designer
- Construction Award – only for principal contractors.

In addition, the Client & (Outline) Design Award is available as an integrated Interim Award en route to a Whole Project Award (WPA plus Client & Design as an Interim Award).

CEEQUAL FOR TERM CONTRACTS

CEEQUAL for Term Contracts has been specifically created for the assessment of civil engineering and public realm works that are undertaken through contracts over a number of years and in a geographical or operational area.

Example contracts may include highway, rail or sewer maintenance, regular interventions in rivers or drainage channels to maintain channel capacity, and a series of minor new works such as road junction remodelling, track renewals and minor realignments, all undertaken through what we call ‘term contracts’.

With multiple works orders for the individual jobs within the contract, not only is the nature of the work often different from projects, but its procurement and management are also normally different.

For Term Contracts, just one type of Award is available to recognise the achievement of the whole contract team, with Awards in the first and last years of the contract and at least every other year in between.

I.5 Voluntary environmental legislation, ecolabels and other schemes

VOLUNTARY LEGISLATION

EU Ecolabel Regulation

Amongst the horizontal measures, Regulation 66/2010 on the EU Ecolabel scheme should also be mentioned. The regulation introduces a voluntary common EU label for enterprises to use in their marketing of products if these fulfil certain environmental performance criteria. The label can be used for the wide range of products for which Ecolabel criteria exist. This includes some of the equipment and materials for construction and use during operation and maintenance.[1] The scheme is based on common criteria for each type of product and common assessment/verification procedures. The criteria relate to the important environmental impacts over the life cycle of the product in question and may include for example energy consumption, waste generation, emission standards etc. The Ecolabel criteria could be included as requirements in the technical specifications or award criteria for the equipment and materials used by the operator.

Eco-management and audit system (EMAS)

Regulation 1221/2009 concerning an eco-management and audit system (EMAS) establishes a voluntary system open for industrial installations as well as a number of other types of sites for which environmental performance is relevant. The audit concerns sites rather than companies or organisations and requires comprehensive environmental strategies and action plans to be established for each site covering all environmental aspects and with the purpose of continuous improvement of environmental performance. The activities on the site and supporting management systems in the enterprise concerned must be audited, and the enterprise is obliged to issue regular environmental statements that are subject to independent validation. EMAS certification, or any other equivalent certification or other documentation for environmental management, may be used to establish environmental technical capacity at the selection stage, as authorised under Article 48.2 (f) and 50 of Directive 2004/18/EC. Such certification or procedures may also be relevant when assessing compliance with technical specifications, award criteria or contract performance clauses – although at these stages it is the specific proposals for carrying out the contract which are being assessed, rather than general organisational profile or capacity (EC, 2010).

ECOLABELS

Ecolabels in EU Countries

<u>The Netherlands</u>

Milieukeur, the Dutch national Ecolabel has developed criteria on concrete products such as slabs and tiles – “Betonbanden, betonstraatstenen en betontegels”. (SMK, 2012). The environmental criteria are concerned with the share (weight percentage) and type of coarse concrete material used in the final concrete product.

<u>Hungary</u>

Hungary has developed an Ecolabel[2] for Bituminous road pavements and road surface coats for maintenance.

The Hungarian label states that energy consumption throughout the lifecycle of the product (from raw material production to paving) should be 10 % less than that of an equivalent product manufactured by the traditional method. Alternatively, if the product offers an additional technical or financial advantage than the equivalent, such as a longer lifetime, then the total energy consumption shall be at least identical to the traditional product.

The label also requires that noise emissions must not exceed the effective limits during the whole procedure of producing road pavement.

Furthermore, a waste-reducing technology shall be used for manufacturing the bituminous mixtures. It also requires documentation to be kept on the waste recycled for use as secondary raw material. Finally, the modifying agent in modified bitumen must be recyclable. (EC, 2010)

Ecolabels in non-European countries

Also countries outside Europe have developed labels for materials used in road construction.

1 For a catalogue of the various products for which the EU Ecolabel is available, see http://ec.europa.eu/ecat/

2 http://www.kornyezetbarat-termek.hu/index.php

Japan

The Japanese Eco Mark criteria have been developed for products used in civil engineering[3]. The criteria are related to specific materials, including cement, aggregates and additives, concrete products and pavement materials including rubber pavement materials and recycled sub-base materials and recycled asphalt mixture. Start and end dates are not provided for the validity of the criteria which focus on recycled content and quality criteria.

The label requires that products must not extract harmful substances including heavy metals, cadmium, lead, hexavalent chromium, arsenic, total mercury, and selenium, during construction or use. It also outlines percentages for recycled content for a variety of products.

Korea

The Korean Ecolabel[4] has also been in existence since 1992. It is a voluntary standard run by the Ministry of Environment. Since 1995 Korean public services have been obliged to buy products with the Ecolabel in compliance with the Act on the Promotion of the Purchase of Environmentally-Friendly Products. There are three Korean ecolabels relevant to road construction materials:

- Water-permeable Concrete Pavements
- Water proofing agents for Construction
- Recycled Construction Materials
- Recycled Slag Products.

The criteria include requirements for recycled content, hazardous waste content and quality specifications.

The label for recycled construction products provides recycled content recommendations for the manufacturing stage of different types of waste material. The label also specifies the installation and operation of a recycling system that recovers used water for reuse.

EPD

The International EPD® System is aimed at helping and supporting organisations to communicate the environmental performance of their products in a credible and understandable way. The International EPD® System is:

- offering a programme for any interested organisation in any country to develop and communicate EPDs according to ISO 14025:2006 and EN 15804:2012, carbon footprint of products according to ISO/TS 14067:2013, and
- supporting other environmental declaration programmes (national, sectorial, etc.) in seeking cooperation and harmonisation and helping organisations to broaden the use of their environmental declarations on an international market.

The Swedish Environmental Management Council act as the programme operator, provide personnel for the Secretariat and has the overall responsibility of International EPD® System.

The International EPD® System is a member of the Global Type III Environmental Product Declarations Network (GEDnet) and cooperates to achieve the GEDnet objectives. The International EPD® System also collaborates with other programme operators acting according to ISO 14025 on topics such as Product Category Rules (PCR) harmonisation.

In the framework of EPD® System, it has been developed a PCR for highways (except elevated highways), streets and roads, according to the UN sub classification CPC 53211 (for further information, see Annex III Table III.2**Error! Reference source not found.**).

This PCR was produced within the Basic Module Land transport infrastructure by the Swedish Transport Administration in collaboration with the Norwegian National Rail Administration (Jernbaneverket), the Norwegian Public Roads Administration (Statens Vegvesen), and the companies WSP Sverige AB, MiSA A, Tyréns, Asplan VIAK AS

The PCR requests a set of technical data that might be relevant for definition and categorization:

- Annual average daily traffic (AADT)
- Road type (e.g. freeway, highway)

3 http://www.ecomark.jp/english/nintei.html

4 http://ecolabel.keiti.re.kr/enservice/enindex.do

- Junctions
- Speed limit
- Number of files
- Road width
- Pavement type
- Minimum radius of curvature
- Maximum gradient
- Maximum axle loading
- Bearing capacity
- Traffic Management System characteristics
- Road side equipment such as traffic barriers and road lightning and
- Regular need of operation and maintenance

The location, boundaries and design of the infrastructure system (share of open section, share of tunnel section, and share of bridge section) shall also be described. The information may be based on a network statement.

Other information requested is the following

- Trade name (if found relevant)
- Unequivocal identification of the product according to the CPC classification system
- Short description of the organisation, including information on products- or management system-related certifications (e.g. ISO Type I ecolables, ISO 9001- and 14001-certificates, EMAS-registrations etc.) and other relevant work the organisation wants to communicate (e.g. SA 18000, supply-chain management, social responsibility - SR etc.)
- Description of the intended use
- All assumptions regarding life times, reinvestment intervals, service intervals etc. shall be defined and summarized in the EPD.
- The relevant functional unit or declared unit, and
- Short description of the underlying LCA-based information (e.g. summary of an existing LCA study or similar studies).
- Geology, geography and climate may be described if relevant.

The functional unit is set as 1 km of main road and year.

To clarify the modules with the flow chart, the following definitions are provided:

Production Road pavement: Includes all products and building processes needed for the construction of the road pavement. Examples of products and processes: bitumen/cement/steel/gravel production, asphalting, drainage and water channels, etc.

Production Road substructure: Includes the production of any associated strengthening materials used in the road foundation and construction processes used to construct the road subgrade itself. Examples of products and processes: soil and rock excavation, crushing of rock, pile driving, production of piles, ballast etc.

Production Road equipment: Includes all products and building processes for installations that is needed for safe operation of the road, but that is not included in the subsystems above. Examples of products and processes: protective devices (parapets, noise barriers, wildlife fences etc.), rest stops, control points, bus stops, drainage, traffic signals, lightning points etc.

Production Road informatics devices: Includes all products and building processes for installations that is needed to monitor traffic in any way, and is not included in the subsystems above. Examples of products and *processes: automatic road safety control systems (camera, data transfer equipment, electric installations etc.), traffic counting devices, weighing appliances, weather information devices etc.*

Production Tunnels: Includes all products and building processes needed for constructing tunnels of any type (rock or concrete constructions). Examples of products and processes: soil and rock excavation, crushing of rock, blasting, explosives, shotcrete, rock bolts, lining, injection moulding, concrete, steel reinforcement, fire protection materials, ventilation systems (pipes, fans etc.).

Production Bridges: Includes all products and building processes needed for constructing bridges of any type (concrete, steel, wood, or aluminum constructions). Examples of products and processes: concrete/steel beams, bridge deck elements, bridge deck waterproofing products and kits (e.g. mastic asphalt, prefabricated membranes, preformed bituminous sheets, resins/polyurethane), injection moulding, iron/steel tension cables, retaining walls etc.

Operation: Includes all the functions needed for operating the infrastructure. Examples of processes: road side lighting, cleaning, salting, graveling etc.

Maintenance: Includes all the functions needed for maintenance of the infrastructure. Examples of processes: drainage of trenches/ditches, planning and gluing of road surfaces.

Re-investments: Includes all activities involved in replacing a road infrastructure part or object by the same or similar type of part or object. For example replacement of pavement.

Cut-off criteria to be met on the level of the product system are the qualitative coverage of at least 99% of the energy, the mass, and the overall relevance of the flows.

I.6 Stakeholder feedback: legislation

Table I.3: Legislative requirements

Waste (all as amended) (UK) • Environment Act 1995 • Environmental Protection Act 1990 • The Controlled Waste (England and Wales) Regulations 2012 • The Waste (England and Wales) Regulations 2011 • Control of Pollution (Amendment) Act 1989 • The Environmental Civil Sanctions (England) Order 2010 • Clean Neighbourhoods and Environment Act 2005 • The Waste Electrical and Electronic Equipment Regulations 2006 – albeit probably out of scope • The List of Wastes (England) (Amendment) Regulations 2005 • The Hazardous Waste (England and Wales) Regulations 2005 • The Waste Management (England and Wales) Regulations 2006 • The Site Waste Management Plans Regulations 2008 • Producer Responsibility Obligations (Packaging Waste) Regulations 2007 • The Packaging (Essential Requirements) Regulations 2009 • The Waste Batteries and Accumulators Regulations 2009 SI 890 – albeit probably out of scope • The Environmental Permitting (England and Wales) Regulations 2010 Materials management (bit tenuous these - all as amended) • Control of Substances Hazardous to Health Regulations 2002 • The REACH Enforcement Regulations 2008
According to European legislation (CPD/CPR and PPD) and standards (harmonized and optional European standards) (DK) Vejregler (Road standards): http://vejregler.lovportaler.dk/ (voluntary but to a large degree followed) Noise: Vejledning fra Miljøstyrelsen nr. 4, 2007 (Støj fra veje) (only recommended values but to a large degree followed) Rolling resistance: No regulation
(IT) *Functional and geometric parameters* • **Ministry Decree 19th april 2006** – Functional and geometric norms for crossroads construction. • **Ministry Decree 22th april 2004** - Modification of Ministry Decree 1st november 2001 - Functional and geometric norms for roads construction: modification of art. 2-3. • **Ministry Decree 1st november 2001** - Functional and geometric norms for roads construction. *Road construction and protection* • **Decree 285/1992** *Road code* (up-to-date to 20th feb 2013 - artt. 13-45). *Safety parameters* • **Ministry Decree 18th february 1993** - *Technical instructions for design, uniformity and use of safety barriers*. • **Ministry Decree 3th june 1998** - *Up-to-date of technical instructions for design, uniformity and use of safety barriers, and technical instruction for safety test methods.* • **Ministry Decree 21th june 2003** - *Up-to-date of technical instructions for design, uniformity and use of safety barriers, and technical instruction for safety test methods*. • **Ministry Decree 25th august 2004.** *Directive on design, installation, check and maintenance of safety systems in road construction*. *Noise parameters* • **Ministry Decree 30th march 2004** *Instruction for limiting and reducing acoustic pollution from road traffic* *Local authority* Province of Trento Del. G.P. n° 41/2012 – provincial decree introducing the GPP for road and other projects for public administrations and Del. G.P. n° 1333/2011 – provincial decree approving the technical standards for the road constructions. These two decrees refer to the C&DW category. Regarding the laboratory technical standards on the recycled aggregates: UNI EN 933, UNI EN 1097, UNI EN 1367, UNI EN 13285, DM 05/02/98 all. 3 (Italian national law), UNI CEN ISO/TS 17892, UNI EN13286 , UNI EN 1744, UNI EN 13286, UNI EN 12697, UNI EN 932, UNI EN 1744, UNI EN 12697 and other (all included in the "norme tecniche per la produzione dei materiali riciclati e posa nella costruzione e manutenzione di opere edili, stradali e recuperi ambientali "). Regarding the road foundation: UNI EN 13286-2, CNR 146 (national research council standards)
In Flanders, VLAREA legislation sets criteria for recycled materials in order to be considered as a construction material.
In Turkey , two key ones are Law no. 3465 of June 2, 1988 regarding the construction, maintenance and operation of highways by entities other than the General Directorate of Highways, and Law no. 3996 of June 13, 1994 regarding the realization of certain infrastructure and public services with the build-operate-transfer model and the related Council of Ministers decree no. 2011/1807 implementing the Law no. 3996.
EN 13877 completed with national requirements EU Construction Product Regulation (EU) No 305/2011

<table>
<tr><td>EU CE marking regulation (EC) No 765/2008</td></tr>
<tr><td>Waste Framework Directive (art.5, Dir. 2008/98/EC).
Ferrous slag has been registered in REACH – Reg. 2006/1907/EC
Standards regulating the use of ferrous slag as a constructional material: e.g. EN14227-2, EN15167-1, EN13043, EN13450, Dutch Ministry of Environment (VROM) "The Dutch Soil Quality Decree – Besluit bodemkwaliteit – The Hague, 2007; Zweiter Arbeitsentwurf der Bundesregierung (2011); Verordnung zur Festlegung von Anforderungen fur das Einbringen und das Einleiten von Stoffen in das Grundwassr, an den Einbau von Ersatzbaustoffen und fur die Verwendung von Boden und bodenahnlichem Material, Januar 2011; Guide methodologique – Acceptabilité de matériaux alternatifs en technique routiére Evaluation environmentale; SETRA April 2011).</td></tr>
</table>

Table I.4 1.Relevant legislation banning the use of specific substances in materials for Road Construction in MS

<table>
<tr><td>The Asbestos (Prohibitions) Regulations 1992 (Prohibitions Regulations) – albeit probably out of scope (UK)</td></tr>
<tr><td>There are legal requirements for dangerous substances, like leaching, radiation, asbestos, tar. Materials not fulfilling those requiremenst are not allowed to be used. There is a total ban for instance on the use of tar and asbestos. (different legal requirements are responsible for that but also based on occupational health criteria (NL)</td></tr>
<tr><td>Recycled Aggregates (IT)
• Ministry Decree 5th february 1998 – Identification of not dangerous waste subject to simplified procedure of recovery (recycling), according to art. 31-32 of Law Decree 5th February 1997.
• Decree 5th april 2006 (n.186) – Regulation concerning modification of Ministry Decree 5th February 1998.
• Minitry Decree 11th april 2011, n. 82 - Regulation concerning management of end-of–life tyres .
Health and Safety of workers in relationship to bitumen and bituminous products -
• Law Decree 81/2008 – technical standard for implementation of art. 1 of Law 3th august 2007 (n.123) concerning health and safety in work places (in relationship to worker risks during asphalt installation for roads and sidewalks).
• Risk profiles in production fields of manufacturing of small and medium-sized industries and public services: asphalters, ISPESL, 2009 (http://www.ispesl.it/profili_di_rischio/asfaltatori/PdR_Asfaltatori.pdf).</td></tr>
<tr><td>Please look at the information provided in the database CP-DS for Germany under the following links (although the titles are in German, the information is provided in English) (DE)
-Brandenburgische Technische Richtlinien für die Wiederverwertung von Baustoffen im Straßenbau - Herstellung, Prüfung, Auslieferung und Einbau (BTR RC-StB), Ausgabe 2002/Fassung 2004; Gemeinsame Richtlinien des Ministeriums für ländliche Entwicklung, Umwelt und Verbraucherschutz und des Ministeriums für Infrastruktur und Raumordnung des Landes Brandenburg
• -Technische Lieferbedingungen Gleisschotter
• -Technische Lieferbedingungen für Asphaltgranulat, Ausgabe 2009
• -Technische Lieferbedingungen für Asphaltmischgut für den Bau von Verkehrsflächenbefestigungen
• Technische Lieferbedingungen für Baustoffe und Baustoffgemische für Tragschichten mit hydraulischen Bindemitteln und Fahrbahndecken aus Beton
• -Technische Lieferbedingungen für Geokunststoffe im Erdbau des Straßenbaus
• -Technische Lieferbedingungen für Gesteinskörnungen im Straßenbau, TL Gestein-StB 04
• -Technische Lieferbedingungen für Markierungsmaterialien
• -Technische Lieferbedingungen für Straßenbaubitumen und gebrauchsfertige polymermodifizierte Bitumen
• -Technische Lieferbedingungen für flüssige Beton-Nachbehandlungsmittel, Ausgabe 2008
• Technische Lieferbedingungen und Technische Prüfvorschriften für Ingenieurbauten (TL/TP-ING), Teil 5 Tunnelbau, Abschnitt 5 Abdichtung von Straßentunneln mit Kunststoffdichtungsbahnen, Technische Lieferbedingungen und Technische Prüfvorschriften für Kunststoffdichtungsbahnen und zugehörige Profilbänder (TL/TP KDB)
• -Technische Lieferbedingungen und Technische Prüfvorschriften für Ingenieurbauten, Teil 5 Tunnelbau, Abschnitt 5 Abdichtung von Straßentunneln mit Kunststoffdichtungsbahnen, Technische Lieferbedingungen und Technische Prüfvorschriften für Schutz- und Dränschichten aus Geokunststoffen</td></tr>
<tr><td>A complete ban on asbestos in Turkey went into effect in 2011</td></tr>
<tr><td>- German "LAGA M20":
• LAGA (Länder-Arbeitsgemeinschaft Abfall) = Joint Waste Commission of the Federal States
• M20 (Mitteilung Nr. 20) = explanatory note/regulation No 20
In this regulation, requirements on the material recycling of mineral residues/wastes are defined. The threshold values pursuant to the LAGA regulation on the requirements for recycling mineral raw materials/waste materials must be complied with.
http://laga-online.de/servlet/is/23874/
- Several federal decrees concerning the re-utilization of mineral waste from industrial processes (e.g. slags, ashes) in road construction and earthwork Examples: http://www.umwelt.nrw.de/umwelt/abfall/mineralabfaelle/index.php, http://www.thueringen.de/th8/tmlfun/umwelt/abfall/entsorgung/mineralisch/</td></tr>
</table>

I.7 Standards

Table I.5: European technical committees

Committee CEN/TC	Title	Working groups
227	Road materials	WG 1 Bituminous mixture WG 2 Surface dressing, slurry surfacing WG 3 Materials for concrete roads incl joint fillers and sealants WG 4 Hydraulically bound and unbound mixtures WG 5 Surface characteristics
351	Construction products – Assessment of release of dangerous substances	WG 1 Release from construction products into soil, ground water and surface water WG 2 Emissions from construction products into indoor air WG 3 Radiation from construction products WG 4 Terminology WG 5 Content and eluate analysis in construction products
350	Sustainability of construction works	WG 1 Environmental performance of buildings WG 3 Products Level WG 4 Economic performance assessment of buildings WG 5 Social performance assessment of building WG 6 Civil Engineering works
51	Cement and building limes	WG 14 Hydraulic binders for road bases WG 13 Assessment of conformity WG 16 Artificial hydraulic lime WG 15 Revision of methods of testing cement WG 10 Masonry cement WG 6 Definitions and terminology of cement WG 12 Special performance criteria WG 11 Building lime
167	Structural bearings	
336	Bituminous binders	WG 2 Fluxed bitumen and bituminous emulsions WG 1 Bituminous binders for paving
337	Road operation equipment and products	WG 1 Winter service equipment and products WG 2 Road service area maintenance equipment WG 3 Interface between vehicles and equipment WG 4 Road surface cleaning equipment
396	Earthworks	WG 4 Quality control WG 5 Hydraulic fill WG 6 Hydraulic placement of mineral waste WG 1 General matters WG 2 Soil and rock classification for Earthworks WG 3 Construction procedures
154	Aggregates	WG 10 Armourstone SC 6 Test methods WG 11 Railway ballast WG 13 Dangerous substances WG 12 Aggregates from secondary source SC 2 Aggregates for concrete, including those for use in roads and pavements SC 1 Aggregates for mortars SC 3 Bituminous bound aggregates SC 5 Lightweight aggregates SC 4 Hydraulic bound and unbound aggregates
104	Concrete	WG 10 Sprayed concrete WG 9 Silica fume for concrete WG 11 Fibres for concrete WG 15 Ground granulated blast furnace slag WG 14 Concrete in contact with drinking water WG 5 Mixing water for concrete SC 2 Execution of concrete structures SC 1 Concrete - Specification, performance, production and conformity SC 3 Admixtures for concrete

Committee CEN/TC	Title	Working groups
		WG 4 fly ash for concrete SC 8 Protection and repairs of concrete structures
178	Paving units and kerbs	WG 1 – Precast concrete products WG 2 – Natural stone products WG 3 – Clay products WG 4 – Test methods for simulation of ageing of pavers by polishing WG 5 – Tactile paving
189	Geosynthetics	WG 4 Hydraulic testing WG 5 Durability WG 6 Geosynthetic barriers - General and specific requirements WG 1 Geotextiles and geotextile-related products - General and specific requirements WG 2 Terminology, identification, sampling and classification WG 3 Mechanical testing
226	Road equipment	WG 9 Clockwork parking meters and automatic car park ticket dispensers WG 6 Noise reducing devices WG 11 Variable message signs WG 10 Break-away safety WG 2 Horizontal road signs WG 1 Crash barriers, safety fences, guard rails and bridge parapets WG 4 Traffic control WG 3 Vertical signs
229	Precast concrete products	
250	Structural Eurocodes	

I.8 Standards: Relevant standards for materials in road construction in the EU

Road construction involves a number of different materials. The major materials can be listed as:

- Asphalt
- Cement
- Concrete (Cement concrete or asphalt concrete)
- Aggregates

All of these materials are well covered by harmonised EN standards and come under the Construction Products Regulation (CPR 2011), which came into force in July 2013. Two big issues with CPR are conformity assessment / constancy of performance and the requirement for a declaration of the potential release of dangerous substances to the environment.

Conformity assessment tasks and related responsibilities of the manufacturer are normally provided in Annex ZA of the relevant EN standard (may not yet appear in older standards). This is linked to verification and auditing systems which are very useful for GPP.

The declaration required for the potential release of dangerous substances to the environment is an area that is still evolving. Many construction materials that are known to contain dangerous substances do not yet have test methods agreed upon that would measure potential release of such substances against specified limits.

a) Asphalt

The requirements for asphalt in the EU are covered by the EN 13108 series of standards. They have a two-tiered approach (empirical based and performance based). The empirical approach (more prescriptive) is adopted for most types of asphalt with the expectation that, as experience improves, a shift towards a performance based (less prescriptive) approach can be made.

Constituent materials in asphalt generally need to comply with relevant EN standards or European Technical Approval reports. However, in the cases of a number of additives such as inorganic and organic fibres, pigments, waxes etc., where not such standards exist, a demonstrable history of satisfactory use exists is sufficient to justify their inclusion.

The three main types of binder that are used in asphalt road pavements are:

- Paving grade bitumen (EN 12591).
- Modified bitumen (EN 14023).
- Hard grade bitumen (EN 13924).

Also there are a number of different types of asphalt mixture that can be used, which include:

- **Asphalt concrete (EN 13108-1).** Asphalt in which the aggregate particles are continuously graded or gap-graded to form an interlocking structure.
- **Asphalt Concrete for very thin layers (EN 13108-2).** Asphalt for surface courses with a thickness of 20 mm to 30 mm, in which the aggregate particles are generally gap-graded to form a stone to stone contact and to provide an open surface texture.
- **Soft asphalt (EN 13108-3).** A mixture of aggregate and soft bitumen grades conforming to EN 12591:1999, Tables 2 or 3. Used widely in cold climates (Nordic countries).
- **Hot rolled asphalt (EN 13108-4)**. A dense, gap graded bituminous mixture in which the mortar of fine aggregate, filler and high viscosity binder are major contributors to the performance of the laid material - can be used in surface courses, binder courses, regulating courses and bases.
- **Stone mastic asphalt (EN 13108-5).** Gap-graded asphalt mixture with bitumen as a binder, composed of a coarse crushed aggregate skeleton bound with a mastic mortar – mainly used in surface courses.

- **Mastic asphalt (EN 13108-6).** Voidless asphalt mixtures with bitumen as a binder in which the volume of filler and binder exceeds the volume of the remaining voids in the mix – can be used in surface and binder courses.
- **Porous asphalt (EN 13108-7).** Bituminous material with bitumen as a binder prepared so as to have a very high content of interconnected voids which allow passage of water and air in order to provide the compacted mixture with drainage and noise reducing characteristics – used for surface courses and can be laid in more than one layer.
- **Reclaimed asphalt (EN 13108-8).** Asphalt reclaimed by milling of asphalt road layers, by crushing of slabs ripped up from asphalt pavements or lumps from asphalt slabs and asphalt from reject and surplus production. Discussed in more detail later.

Different grades of bitumen binder will be specified for different types of asphalt as stated in the relevant parts of EN 13108 listed above. However, all types of asphalt used in road construction generally have the same applicable technical and performance criteria. Most technical criteria also contain a "**No Requirement**" class (NR). This means that the asphalt for a particular given use does not need to meet that particular criterion or at least does not need to be tested for it.

The term "*as appropriate for the intended use*", is common across the EN 13108 standards and is open to interpretation as being "*deemed according to the expected traffic density, climatic conditions, underlying road course and economic considerations*". A summary of the main technical criteria for asphalt are included in Table _ below.

Table I.6: A summary of the main technical standards for asphalt mixtures

Property/Criteria	**Standard**	**Requirement and comments**
Binder used	EN 12591	For paving grade bitumen, modified bitumen and hard grade bitumen respectively. Grade and % mass of binder shall be declared (EN 13108).
	EN 14023	
	EN 13924	
Needle penetration or softening point	EN 1426	For paving grade bitumen where >10% reclaimed asphalt is used in **surface courses***. Must still meet the requirements for relevant grade.
Needle penetration or softening point	EN 1426	For paving grade bitumen where >20% reclaimed asphalt is used in **regulating courses****. Must still meet the requirements for relevant grade.
Aggregates	EN 13043	Includes coarse aggregate, fine aggregate and all-in aggregates. Potential for use of secondary materials.
Added filler	EN 13043	The quantity used shall be declared and may include cement and hydrated lime.
Reclaimed asphalt	EN 13108-8	The amount used shall be declared. Criteria directly applied to reclaimed asphalt are discussed in more detail later.
Additives	-	Shall be declared and deemed suitable by legislation, local regulations and/or previous experience. % mass shall be declared.
Grading	EN 13043	The grading of binder particles shall meet the requirements for the particular grade of asphalt used.
Void content and voids filled with bitumen	EN 13108-20, EN 12697-6 & -8	Requirements vary depending on the type and grade of asphalt mixture used.
Water sensitivity	EN 12697-12	Specimens prepared according to en 13108-20. This test can be applied to all types of asphalt.
Resistance to abrasion by studded tyres	EN 12697-16	Specimens prepared according to en 13108-20
Resistance to permanent deformation.	EN 12697-22	Specimens prepared according to EN 13108-20. Only applies to Asphalt concrete, hot rolled asphalt and stone mastic asphalt mixtures.
Reaction to fire	EN 13501-1	Only required if road is subject to certain regulatory requirements in place of use.
Mixture temperature	EN 12697-13	Limits depend on the bitumen grade used.

*surface courses represent the uppermost layer of the road, in direct contact with traffic.

**regulating courses are courses of variable thickness that are used on top of subgrades, bases or other courses to alter the profile, facilitating the placement of another course, of consistent thickness, directly above.

A number of other criteria such as stiffness, fatigue, binder drainage and permeability are not included above since they only apply to one or two or the asphalt types listed earlier. Tests unique to asphaltic mixes used in airfields have not been included in Table _ since this has not been included within the scope for GPP of road construction, as it will be explained in section 1.5.

Reclaimed asphalt

In terms of improvement potential and environmental impacts, an important parameter for GPP is the possibility to use reclaimed asphalt. There is no technical limit on reclaimed asphalt content in new asphalt mixtures so long as adequate performance is achieved. However, any reclaimed asphalt will have to comply with the following criteria listed in Table I.7

Table I.7: Criteria for reclaimed asphalt

Property/Criteria	Standard	Requirement and comments
Foreign matter	EN 12697-42	Considers 2 groups of materials: (1-cement concrete, bricks, sub base material, mortar, metal) and (2-plastics, wood, synthetics). The content of foreign matter must be declared.
Binder properties	EN 12697-3 or EN 12697-4	Binder extracted from reclaimed asphalt and tested for penetration (EN 1426), softening point (EN 1427) or viscosity (EN 12596).
Binder type	-	Shall be declared and based on tests or knowledge of asphalt source.
Aggregate grading	EN 13043	By sieve analysis testing.
Binder content	EN 12697-1	Value shall be declared. Important for future mix design.
Homogeneity	-	Based on the variability of binder property and aggregate grading results. A declaration may be required by client.

b) Cement

A number of different types of cement are available on the market with different hydration chemistries such as Calcium Aluminate and Sulfoaluminate belite cements. However, these are considered as "speciality cements" and only used in niche applications. One such niche may be road surface repair and will be briefly discussed later in this report. The most economical and dominant cement worldwide is Portland cement. This dominance applies also to road construction.

Portland cement is traditionally known as a combination of Portland cement clinker (ca. 95%) and gypsum (ca. 5%) that have been milled together to produce a fine and homogenous powder. Decades of scientific research have shown that a number of other materials can be blended with Portland cement without detracting from cement performance. Indeed, in some cases technical performance is enhanced. Such materials are commonly referred to as "supplementary cementitious materials" (SCM's).

Within the EU, Portland cement is classified into 1 of 27 categories according to EN 197-1, depending on the degree of blending with different SCM's. These categories are split among 5 broader groups; CEM I, CEM II, CEM III, CEM IV and CEM V. The possibility to use SCM's offers the potential to significantly reduce the environmental footprint of Portland cement. The EN 197-1 standard specifically allows for up to 10% by dry mass silica fume, up to 35% limestone, up to 35% burnt shale, up to 55% mixtures of silica fume/coal fly ash/natural pozzolana or up to 95% blast furnace slag in blended cements. Other unspecified potential additives are also permitted up to 5% by dry cement weight. All of the specified SCM's effectively reduce the embodied energy and CO_2 footprint of the blended cement product (CEM II-V) compared to normal Portland cement (CEM I) (see section 3.__). Consequently, EN 197-1 is an important standard to consider in terms of improvement potentials in road construction.

EN 197-1 allows for a great variety of tailored cement formulations to be marketed in the EU. In most cases, the precise mixture of materials in a given blended Portland cement product is sensitive information and is withheld from the client. However, the producer must state which of the 27 categories listed in EN 197-1 the product belongs to and this gives an approximate idea of the possible blended cement composition. Furthermore, all marketed Portland cements must meet any relevant technical requirements for cement performance as per methods specified in the series of EN 196 standards (see Table I.8 and Table I.9)

Table I.8: Compressive strength (as mortars) and initial setting time requirements (as pastes**) for Portland cement given in EN 197-1.*

Strength class	**Compressive strength (MPa) measured as per EN 196-1**				**Initial setting time (mins) as per EN 196-3**
	Early strength		Standard strength		
	2 days	7 days	28 days		
32.5 L†		≥ 12.0	≥ 32.5	≤ 52.5	≥ 75
32.5 N	-	≥ 16.0			
32.5 R	≥ 10.0	-			
42.5 L†	-	≥ 16.0	≥ 42.5	≤ 62.5	≥ 60
42.5 N	≥ 10.0	-			
42.5 R	≥ 20.0	-			
52.5 L†	≥ 10.0	-	≥ 52.5	-	≥ 45
52.5 N	≥ 20.0	-			
52.5 R	≥ 30.0	-			

*mortars are mixtures of 3 parts sand to 1 part cement plus mixing water,

**pastes are simply mixtures of cement with mixing water,

† class L strength limits are only applicable to CEM III type cements.

As shown in Table 1, the minimum allowed setting time for Portland cement pastes varies from ≥45 minutes to ≥75 minutes, depending on the strength class of the cement.

From Table I.8 above, it can be understood that the minimum compressive strength requirement of any marketed Portland cement formulation (in mortar mixes) is 16.0 MPa after 7 days hydration under standard conditions defined in EN 196-1 (or 12.0 MPa with CEM III type cements). A further requirement is that compressive strength later reaches at least 32.5 MPa after 28 days hydration.

The EN 197-1 standard also specifies a number of other criteria, measured according to methods specified in the EN 196 series of standards, which marketed Portland cement must comply with. This is summarised briefly in Table I.9 below.

Table I.9: List of EN 196 methods for testing of Portland cement and limits mentioned in EN 197-1.

Criteria	**EN 197-1 limit(s)**	**EN 196 method**	**Comments**
Compressive strength	See table 1	EN 196-1: Determination of strength.	Applies to 3:1 mortars made in prismatic moulds of 4x4x16cm and cured under standard conditions. Also specifies the strength
Sulfate content (as SO3)	Maximum limit 3.5% or 4.0% depending on the CEM type and strength class of cement.	EN 196-2: Chemical analysis of cement. Specifically section 4.4.2.	Method is gravimetric determination via precipitation as Barium sulfate.
Insoluble residue	Maximum limit 5.0%. Only applies to CEM I and CEM III cements.	EN 196-2: Chemical analysis of cement. Specifically section 4.4.3.	Method involves use of hydrochloric acid + sodium carbonate or potassium hydroxide.
Loss on Ignition	Maximum limit 5.0%. Only applies to CEM I and CEM III type cements.	EN 196-2: Chemical analysis of cement. Specifically section 4.4.1.	Dry cement sample is fired at 950°C during 15 minutes. Correction for any sulphide present is necessary.
Chloride	Maximum limit 0.10%. Applies to all cements although exemptions may be applicable to CEM III type cement.	EN 196-2: Chemical analysis of cement. Specifically section 4.5.16.	Method involves pre-treatment with nitric acid and reaction with silver nitrate.
Initial setting time	Must be longer than either 45, 60 or 75 minutes, depending on the strength class of cement.	EN 196-3: Determination of setting times and soundness	Using the Vicat needle method on pastes. Initial setting defined as when the needle penetration reduces from 40mm to 34mm (+/-3mm).
Soundness	Expansion must be less than 10mm. Applicable to all cements.	EN 196-3: Determination of setting times and soundness	Uses Le Chatelier apparatus with cement pastes..
Pozzolanicity	Must satisfy the test (positive result). Only applies to CEM IV type cements.	EN 196-5: Pozzolanicity test for pozzolanic cements.	Hydration in a closed container under specified conditions must lead to a solution non-saturated with respect to CaO.
Heat of hydration	To be classified as a low heat output cement, total heat of hydration must be less than 270 J/g cement.	EN 196-8: Heat of hydration – solution method. EN 196-9: Heat of hydration – semi-adiabatic method.	The limit of 270 J/g is applied to the first 7 days of hydration according to the 196-8 method and to the first 41 hours of hydration according to the 196-9 method.

Due to concerns about skin sensitisation of construction workers and other toxic effects of hexavalent Chromium, EU directive **2003/53/EC** specifies that Portland cement should contain less than 0.0002% (2mg/kg) water soluble Chromium (VI) as measured according to **EN 196-10**. Cr(VI) can potentially form in the cement kiln environment from any Cr(III) present in raw materials and from abrasion of steel surfaces during the grinding process. Cements may need to be dosed with reducing agents, such as ferrous sulfate, to ensure compliance with this limit.

c) Concrete

The dominant technical standard at the EU level governing concrete is EN 206: Concrete – Specification, performance, production and conformity. This standard is of particular interest since it outlines the roles and responsibilities of "specifier", "producer" and "user". These roles may belong to different groups or, in the case of certain design and build contracts, belong to the same party.

The "specifier" is typically the party responsible for the design of the road

They are required to communicate to the producer, as a minimum for normal weight concrete:

- the compressive strength class of the concrete,
- the exposure class,
- D_{upper} and D_{lower} (explain this),
- chloride content class (see Table I.10)
- the consistence class or target consistency for site-mixed or ready mixed concrete.

Furthermore, the specifier can make a number of optional further requirements, which are especially useful in terms of reducing the environmental impact of concrete. These include:

- specific types or classes of cement to use in concrete
- specific types or categories of aggregate (in this case the specifier assumes responsibility any subsequent deleterious alkali-silica reaction).
- Heat development during hydration
- Resistance to abrasion and many other technical criteria.

The "user" is the party that places the concrete on site

They are required to:

- Agree a delivery date and time for concrete delivery.
- Agree upon the quantities and rate of concrete delivered.
- Inform the producer of any special transport requirements on site.
- Inform the producer of any special placement methods to be used.

The "producer" is the company that provides the concrete mixture to the user

They are required to produce upon request by the user the following information:

- The type and strength class of cement used.
- The type of aggregates used.
- The type of admixtures and additions used, if any.
- Results of relevant previous tests for conformity control of concrete to the specifiers requirements and other relevant requirements.
- Information on the rate of strength development of concrete up to 28 days at 20°C.
- The sources of constituent materials.
- Any relevant health and safety information to workers handling concrete.

By following the requirements of EN 206, a clear procedural system is made available by which clients, either directly or via a "specifier" intermediary, can clearly define the type of concrete desired and the specific constituents of the concrete. For lifecycle assessment purposes, it is especially useful that the producer can be obliged to reveal the source of the concrete constituents when considering transport costs and impacts. Annex C of EN 206 provides a framework for assessment, verification and certification of the concrete "producer" which can be incorporated into individual civil works contracts.

The general manner in which EN 206 is related to other relevant EU standards is illustrated in Figure I.3 below.

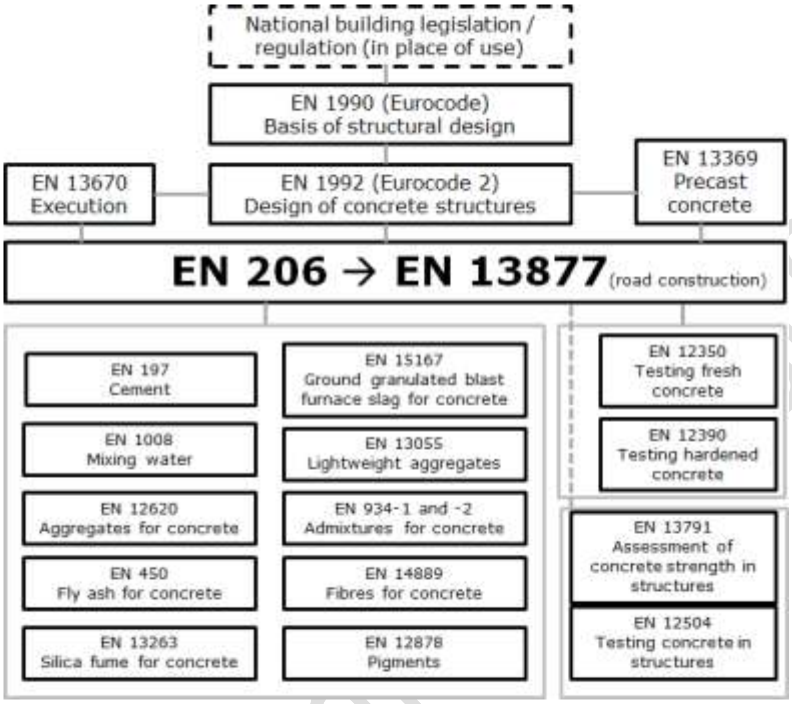


Figure I.3: Relationship between EU standards for concrete (as shown in EN 206).

When dealing with road construction, EN 206 directs the reader specifically to EN 13877. However, many of the standards related to concrete in EN 206 are important when identifying the improvement potential for road pavement construction. The use of industrial by-products like fly ash and blast furnace slag are likely to be important considerations in developing potential GPP criteria. The requirements for fly ash and blast furnace slag to be used in EN 206 concrete are shown in Table I.10.

EN 13877 states that all materials used in concrete pavements must be as specified in EN 206 (i.e. cement as per EN 197-1, any fly ash as per EN 450-1, aggregates as per EN 12620 and blast furnace slag as per EN 15167 and so on). Exceptions to constituent materials are permitted only where a European Technical Approval exists for the use of any non-specified constituent or where relevant national standards or provisions exist regarding the non-specified constituent in the place where construction is to take place.

With regards to properties of fresh concrete, the requirements of EN 13877-1 can be summarised in Table I.10:

Table I.10: EN 13877 requirements for fresh concrete

Criteria	Requirement	Test involved (ref)	Concrete class	Comments
Consistence	Must meet condition of "specifiers". Can be achieved by 1 of 4 different tests.	Slump test EN 12350-2	S1 – S5	Each class corresponds to a specific result for a specific test. Further criteria apply for self compacting concrete.
		Compactibility test EN 12350-4	C0 – C4	
		Flow test EN 12350-5	F1 – F6	
		Slump flow test EN 12350-8	SF1 – SF3	
Density	For normal weight concrete, the oven dry density must be 2000-2600kg/m^3 or within 100kg/m^3 of a specified target density value.	EN 12390-7	Normal weight concrete.	Other criteria apply for lightweight and heavy-weight concrete, but this is not generally applicable to road construction.
Air content	Optional and only if specified.	EN 12350-7	For normal weight concrete.	Relevant to freeze-thaw resistance.
Cement content	In accordance with specified value.	Batch quality control at concrete plant.		Minimum limit of 10kg/m^3 below specified amount.
Chloride content	Maximum 0.40% per mass of cement.	EN 196-2 (in cement) EN 12620* and EN 1744-5 (in aggregates)		Test method varies according to the individual constituent tested.

*more information on aggregate specifications is included in the next section.

With regards to the properties of **hardened** concrete, the criteria requirements in EN 13877-1 include the following (Table I.11):

Table I.11: EN 13877-1 and -2 requirements for hardened concrete

Criteria	Requirement	Test involved (ref)	Concrete class	Comments
Freeze-thaw resistence	Where road concrete is considered to be at significant risk of freeze-thaw attack. As per clients specification (if applicable).	Freeze-thaw cycling, CEN/TS 12390-9, or relevant national standard in place of construction.	FT0 – FT2 (as mentioned in EN 13877-2)	This will obviously depend on climatic conditions which vary widely across the EU.
Wear resistance to studded tyres	As per clients specification (if applicable).	Wear Resistance Index as per EN 13863-4	WR0 – WR4	Applicable where concrete is the surface layer of road.
Bond strength	As per clients specification (if applicable).	EN 13863-2	A typical value is ca. 1.0MPa for guidance.	When two different layers of concrete have been poured.
Mechanical strength	The requirement strength class or classes for the concrete shall be per client specifications. Results can be generated using specimens cured in moulds or from cores taken from the actual concrete poured on site. In the latter case, cores shall be taken in accordance with EN 13877-2 (specifically section 4.2).	Compressive strength EN 12390-3	C8/10 – C100/115 "recommended" to be at least class C20 for cylindrical cores.	Values range from 8-100MPa for cylinder specimens and 10-115MPa for cubes. Other classes apply for lightweight concrete.
		Tensile splitting strength EN 12390-6	S1.3 – S6.0 "recommended" for cores to be at least SC1.7.	Classes correspond to 28d samples and strengths of 1.3-6.0 MPa.
		Flexural strength EN 12390-5	F2 – F10	Classes correspond to 28d samples and strengths of 2 – 10 MPa.
Concrete thickness	To be within -5 and +15mm of tolerance of specification.	Core sampling EN 13877-2		At least 3 cores taken to verify the results of the non-destructive test.
		Non-destructive survey method EN 13863-1		
Concrete density	Shall not be less than 95% of the specified density.	EN 12390-7		Applies to saturated cores of road layer.
		As per EN 12350-1, 12390-1 and 12390-2		Applies to fully compacted moulded specimens.

A number of other materials are important in the final performance of road concrete. These include chemicals used in the concrete curing process, resistance of the concrete and the use of steel components used to reinforce the concrete and transfer loads smoothly between different slabs. A summary of the key factors covered in EN 13877-1 and 2 is included in Table I.12:

Table I.12 - Requirements for other materials used in concrete road construction

Criteria	Requirement	Test involved (ref)	Comments
Curing materials	As per agreement between user, producer and specifier.	No test, simply to be approved by (CEN/TS 14754-1) and/or relevant national standards	Applied to exposed concrete surface to minimise moisture loss.
Surface retarders	Only required when exposed aggregate surface finishes are specified.	No test. Simply that the chemical used has been proven by experience to be suitable.	Must either prevent concrete surface drying or be covered with a plastic sheet.
Joint sealants	Compliance with relevant standards.	(EN 14188-1, -2 and -3)	
Tie bars	Smooth tie bars to be at least class B250	Diameter 10-20mm and length 800mm. Conform with (EN 10080).	Protective measures against corrosion of tie bars shall be as per requirements in place of use.
	Deformed tie bars to be at least B500.		
Dowels	Compliance with standard.	(EN 13877-3)	
Rebar	At least grade B500	(EN 10080)	

d) Aggregates

Aggregates are used directly in concrete, where they are bound together by hydrated cement paste, in bases, where they may be bound by hydraulic binders (lime, cement or ground granulated blast furnace slag) or in bituminous mixtures. However, in road construction, they can also be used in an unbound form, as inert fill in a compacted subgrade below the road base layers.

These applications (bound and unbound) can accept a certain amount of recycled aggregate, or air cooled blast furnace slag, which is an important consideration with regards to the improvement potential of road construction in GPP.

Some technical definitions of different types of aggregate are as follows:

- **Aggregate**: *Granular material of natural, manufactured or recycled origin used in construction.*
- **Natural aggregate**: *Aggregate from mineral sources which has been subjected to nothing more than mechanical processing.*
- **Manufactured aggregate**: *Aggregate of mineral origin resulting from an industrial process involving thermal or other modification.*
- **Recycled aggregated**: *Aggregate resulting from the processing of inorganic or mineral material previously used in construction*.
- **Fines**: *Particle size fraction of aggregates that pass a 0.063mm sieve.*
- **Coarse aggregate**: *Aggregates of grading where D >4mm and d is ≥1mm*.
- **Fine aggregate**: *Aggregates of grading where D ≤4mm and d = 0.*
- **All-in aggregate**: *A mixture of coarse and fine aggregate where D >4mm and d=0.*
- **Filler aggregate**: *Very fine aggregate, with 100% of particles <2mm and which mostly (>70% by mass as per EN 933-10) passes a 0.063mm sieve can be added to concrete to provide certain properties.*
- **Added filler**: *Filler aggregate of mineral origin, which has been produced separately.*

The 4 main EN standards regarding "bound" aggregates in the EU are shown in Figure I.4. Of these, two are of particular relevance to road construction (circled in red). For sub-bases which use unbound aggregate, the EN 13285 standard is also important, circled in blue.

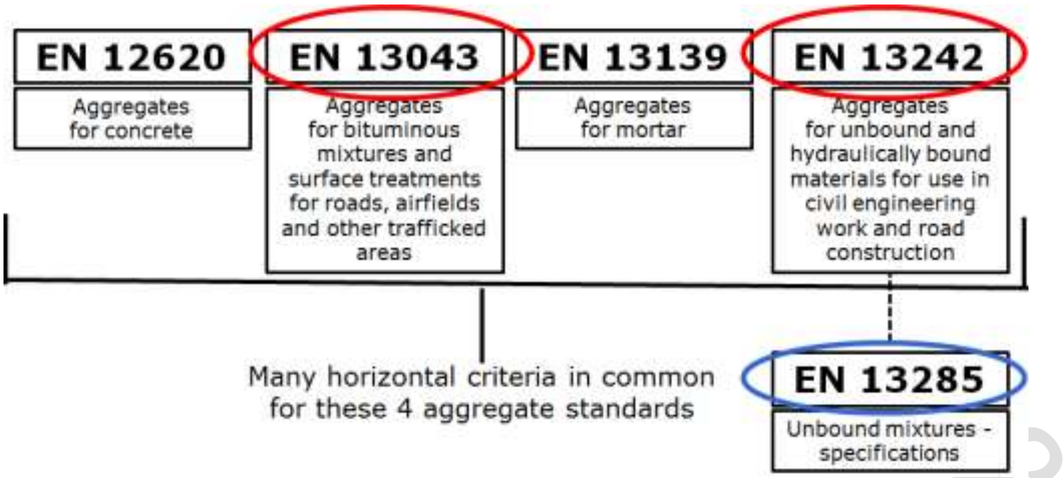


Figure I.4: The four main standards relevant to aggregates in the EU.

Bound aggregates in road construction EN 13043 and EN 13242

Focussing on bound aggregates in road construction, it is only necessary to look at the EN 13043 and 13242 standards in any great detail. Since almost all the same criteria apply to both standards, they are summarised together in the same table below, highlighting if there are any differences in specifications for aggregates in bituminous mixtures (EN 13043) and in unbound/hydraulically bound mixtures (EN 13242).

With regards to unbound aggregates, it is necessary to take into account the EN 13242 and the EN 13285 standards. The latter applies strictly to final mixtures of aggregates whereas the former generally applies to single sources and types of aggregate.

The criteria for aggregates are broadly split into three groups, namely grading (size distributions), physical, chemical and durability criteria.

Table I.13: Physical requirements for aggregates to be used in road construction

Criteria	**Requirement**	**Test method**	**Possible classes listed**		**Comments**
			In EN 13242 (hydraulic bound)	**In EN 13043 (bitumen bound)**	
Resistance to fragmentation	The Los Angeles Coefficient*	EN 1097-2	LA_{20}-LA_{60}, $LA_{Declared}$, LA_{NR}	LA_{15} – LA_{-40}, LA_{50} or LA_{NR}	Higher coefficient means a better resistance. Alternative method suggested for recycled aggregates.
	Impact Value SZ*	EN 1097-2	SZ_{18}-SZ_{38}, $SZ_{Declared}$, SZ_{NR}	SZ_{18}-SZ_{35}, $SZ_{Declared}$, SZ_{NR}	
Resistance to wear	Micro-Deval coefficient*	EN 1097-1	M_{DE15}-M_{DE50}, $M_{DEDeclared}$, M_{DENR}	M_{DE10}-M_{DE25}, M_{DE35},$M_{DEDeclared}$, M_{DENR}	Dry or wet test possible.
Particle density	Only if required by client.	EN 1097-6	Declared value only.	Declared value only.	
Water absorption	Only if required by client.	EN 1097-6	Declared value only.	Declared value only.	
Bulk density	Only if required by client.	EN 1097-3	Declared value only.	Declared value only.	
Water suction height	Only if required by client.	EN 1097-10	Declared value only.	**Not applicable.**	
Resistance to polishing	When used in surface courses. Polished stone value.	EN 1097-8	**Not applicable.**	PSV_{68}-PSV_{44}, $PSV_{Declared}$, PSV_{NR}	
Resistance to surface abrasion	When used in surface courses. Aggregate abrasion value.	EN 1097-8	**Not applicable.**	AAV_{10}-AAV_{20}, $AAV_{Declared}$, AAV_{NR}	
Resistance to abrasion from studded tyres	When used in surface courses. Nordic abrasion value.	EN 1097-9	**Not applicable.**	AN_{5}-AN_{30}, $AN_{Declared}$, AN_{NR}	
Affinity to bituminous binder	Only if required by client.	EN 12697-11 (method A)	**Not applicable.**	Declared value only.	

*The possibility of using class "NR" indicates that in some or all applications, it is not strictly necessary to show compliance with that given property unless specified by the client. Likewise, where no classes exist for a given property, the requirement for a declared value is again only if specified by the client.

Table I.14: Chemical requirements for aggregates to be used in road construction

Criteria	Requirement	Test method	Possible classes listed		Comments
			In EN 13242 (hydraulic bound)	**In EN 13043 (bitumen bound)**	
Petrographic description	Only if specified by client.	EN 932-3	Declared value only.		
Coarse light weight contaminators	Only if specified by client.	EN 1744-1	**Not applicable**	$m_{LPC0.1}$, $m_{LPC0.5}$, $m_{LPCDeclared}$, m_{LPCNR}	Flotation method.
Constituents of recycled aggregates	Only if specified by client.	EN 933-11	All classes for categories, Rc, Ru, (Rc+Ru), (Rc+Ru+Rg), Rb, Ra, Rg, X, (X+Rg) and FL	**Not applicable**	See footnote below table for an explanation of these categories.
Acid soluble sulfate	Only if specified by client.	EN 1744-1	$AS_{0.2}$, $AS_{0.8}$, $AS_{Declared}$, AS_{NR}	**Not applicable**	For non-air cooled blast furnace slag aggregates.
			$AS_{1.0}$, $AS_{Declared}$, AS_{NR}	**Not applicable**	For air-cooled blast furnace slag.
Total Sulfur	Only if specified by client. Stricter limits apply if pyrrhotite (FeS) is present.	EN 1744-1	S_1, $S_{Declared}$, S_{NR}	**Not applicable**	For non-air cooled blast furnace slag aggregates.
			S_2, $S_{Declared}$, S_{NR}	**Not applicable**	For air-cooled blast furnace slag.
Water soluble sulphate in recycled aggregates	Only if specified by client.	EN 1744-1	$SS_{0.2}$, $SS_{0.7}$, $SS_{1.3}$, SS_{NR}	**Not applicable**	Water soluble sulfates are a particular concern in concrete.
Constituents affecting volume stability of unbound slag aggregates	No Iron disintegration of air cooled BFS**	EN 1744-1	Declared value and only if specified	Declared value and only if specified	
	No dicalcium silicate disintegration of air cooled BFS**	EN 1744-1			
	Volume stability of steel slag	EN 1744-1	V_5, $V_{7.5}$, V_{10}, $V_{Declared}$, V_{NR}	$V_{3.5}$, $V_{6.5}$, V_{10}, $V_{Declared}$, V_{NR}	Test time 24h if total MgO <5% or 168h if >5%

Rc = Concrete, concrete products, mortar & concrete masonry units.
Ru = Unbound aggregate, natural stone & hydraulically bound aggregate.
Rb = Clay masonry units (i.e. bricks and tiles), Calcium silicate masonry units & aerated non-floating concrete.
Ra = Bituminous materials.
Rg = Glass.
FL = Floating material (in volume).
X = Other: Cohesive (e.g. clay and soil), Miscellaneous (e.g. ferrous and non-ferrous metals), non-floating wood, plastic and rubber, gypsum plaster.
**BFS = Blast Furnace Slag

Table I.15: Durability criteria for aggregates in hydraulic bound and bitumen bound applications

Criteria	Requirement	Test method	Possible classes listed		Comments
			In EN 13242 (hydraulic bound)	**In EN 13043 (bitumen bound)**	
Magnesium sulphate soundness	Only if specified by client.	EN 1367-2	MS_{18},MS_{25},MS_{35}, $MS_{Declared}$, MS_{NR}	MS_{18},MS_{25},MS_{35}, $MS_{Declared}$, MS_{NR}	Does not apply to recycled aggregates with cementitious content (EN 13242)
Freeze-thaw screening	Absorb less than 1 or 2% by mass H_2O in 24h	EN 1097-6	$WA_{24}1$, $WA_{24}2$	$WA_{24}1$, $WA_{24}2$	Not applicable to blast furnace slag
Freeze-thaw resistance	Only if specified by client.	EN 1367-1	F_1, F_2, F_4, $F_{Declared}$, F_{NR}	F_1, F_2, F_4, $F_{Declared}$, F_{NR}	10x24 hours freeze thaw cycles
Freeze-thaw resistance with salt	Only when specified by client.	EN 1367-6	**Not applicable**	F_{EC50}, $F_{ECDeclared}$	
Sonnenbrand	Only applicable to basalt aggregates	EN 1367-3 and EN 1097-2	SB_{SZ}, SB_{LA}, $SB_{SZDeclared}$, $SB_{LADeclared}$, SB_{NR}	SB_{SZ}, SB_{LA}, $SB_{SZDeclared}$, $SB_{LADeclared}$, SB_{NR}	

Filler aggregate in bituminous mixtures (additional criteria in EN 13043)

The EN 13043 standard also applies a series of criteria for filler aggregate, which essentially corresponds to fine aggregates in the size range 0 – 0.125mm. Since these criteria could be important in terms of incorporating industrial by-products and other secondary materials into the bituminous mixtures used in road construction, key aspects of these criteria are briefly summarised below.

Table I.16: EN 13043 criteria for filler aggregate in bituminous mixtures

Criteria	Requirement	Test method	Classes	Comments
Grading	100% <2mm, ≥85% <0.125mm and ≥70% <0.063mm	EN 933-10	Not applicable	Consistency of product grading by manufacturer required too
Harmful fines	Only if specified	EN 933-9	MB_{F7}, MB_{F10}, MB_{F25}, $MB_{FDeclared}$, MB_{FNR}	Methylene blue test.
Water content	Only if specified	EN 1097-5	WC_1, $WC_{Declared}$, WC_{NR}	
Particle density	Declaration of result	EN 1097-7	Declared value	
Stiffening properties	Only if specified	EN 13179-1	$\Delta_{R\&B}8/16$, $\Delta_{R\&B}17/25$, $\Delta_{R\&B}8/25$, $\Delta_{R\&B}25$, $\Delta_{R\&B}NR$	"Delta ring and ball" value
Water solubility	Only if specified	EN 1744-1	WS_{10}, $WS_{Declared}$, WS_{NR}	
Water "susceptibility"	Only if specified	EN 1744-4	Declared result only	Swelling shall not exceed 1.0% volume in certain cases
Carbonate content	Only if specified	EN 196-2	CC_{f90}-CC_{f60}, $CC_{fDeclared}$, CC_{fNR}	For non-limestone filler, the carbon dioxide method is used. For limestone filler, the Calcium oxide method is used.
Calcium hydroxide content	Only if specified	EN 459-2	Ka_{25}, Ka_{20}, Ka_{10}, $Ka_{Declared}$, Ka_{NR}	Multiple by 1.3213 to express CaO as $Ca(OH)_2$
Bitumen number	Only if specified	EN 13179-2	$BN_{28/39}$, $BN_{40/52}$, $BN_{53/62}$, $BN_{Declared}$, BN_{NR}	
Loss on ignition	≤6%	EN 1744-1	Declared value only	For coal fly ash. Correction factors for non-volatile oxidisable substances may apply.
Particle density	<0.2 Mg/m^3	EN 1097-7	Declared value only	
Loose bulk density	0.5 – 0.9 Mg/m^3	EN 1097-3	Declared value only	In kerosene
Specific surface area	≤140m^2/g	EN 196-6	Declared value only	As per Blaine method. Alternative N_2 absorption method also possible (ISO 9277).

Unbound aggregate mixtures used in road construction (EN 13285)

The aggregates used in unbound mixtures as a general rule must also comply with the physical, chemical and durability requirements set out in EN 13242 (see Table _ above). The standard covers aggregates with a D value of 8mm to 90mm and a d value of 0mm and applies directly to use in road base and road sub-base construction.

The standard focuses on the mixture composition for direct use in construction in unbound applications. The following criteria are specifically listed:

- **Grading of mixture (d/D)**: a total of 15 different grading categories ranging from 0/8 (narrowest) to 0/90 (widest).
- **Fines content**: only when specified will a maximum and/or minimum fines content value (and category) need to be declared.
- **Oversize content**: At least 75% of aggregate mass must be smaller than the specified largest aggregate diameter (D value). The appropriate category must be declared.
- **Grading curve**: For each of the 15 grading categories, a grading curve that can be verified by sieve analysis is provided.

A series of tests that should be applied at an aggregate production factory for quality control purposes are also provided (in Annex C of EN 13285). The dry density of aggregate mixtures and optimum water content (which is very important during the compaction of the road base or sub-base can be determined by one of four specified methods (EN 13286-2, -3, -4 and -5).

The water soluble sulfate content of the aggregate mixture must also be specified when required and may limit use when placed close to concrete depending on national legislation in the place of use.

General factors to consider in GPP for aggregates:

In terms of GPP, important considerations are the **source** (transport impacts) and the **nature** (other environmental impacts) of aggregates specified for road construction. Criteria for aggregates are well established by EN standards but are not overly restrictive, often optional and in many cases allow any national legislation or procedures in the place of work to dominate. The EN requirements should make it easy to determine where an aggregate is sourced from and thus help to calculate for example, whether or not it compensates to source recycled aggregate from 300km away instead of natural aggregate from 100km away. In terms of the nature of recycled aggregates and secondary materials in road construction, it is important for GPP specialists to specify alternatives that have some degree of proven satisfactory performance and assessment. Some alternative aggregates are also currently being investigated for additional technical criteria, which is worth being aware of. The table below summarises experience with secondary aggregate materials in road construction (taken from EN 13242 Annex A).

Table I.17: List of classification codes and status for source materials in EN 13242 aggregates

Source	Subnr.	Specific material	History of use	Special req. in standard	Additional req. identified for inclusion
Natural aggregates	P	All petrographic types included in EN 932-3	Yes	Yes	No
Construction and demolition recycling industries	A1	Reclaimed asphalt	Yes	Yes	No
	A2	Crushed concrete	Yes	Yes	No
	A3	Crushed bricks, masonry	Yes	Yes	No
	A4	Mix of A1, A2 and A3	Yes	Yes	No
Municipal solid waste incineration industry	B1	Municipal incinerator bottom ash (MIBA) (excludes fly ash)	Yes	No	Yes
	B2	Municipal incinerator fly ash (MIFA)	No	-	-
Coal power generation industry	C1	Coal fly ash (FA)	Yes	No	Yes
	C2	Fluidised bed combustion fly ash (FBCFA)	Yes	No	No
	C3	Boiler slag	Yes	No	Yes
	C4	Coal bottom ash	Yes	No	Yes
	C5	Fluidised bed combustion bottom ash (FBCBA)	Yes	No	No
Iron and steel industry	D1	Granulated blast furnace slag (GBS) (vitrified)	Yes	Yes	No
	D2	Air cooled blast furnace slag (ABS) (crystallised)	Yes	Yes	No
	D3	Basic Oxygen furnace slag (converter slag, BOS)	Yes	Yes	No
	D4	Electric arc furnace slag (from Carbon steel production, EAF C)	Yes	Yes	No
	D5	Electric arc furnace slag (from stainless/high alloy steel production, EAF S)	No	-	-
Non-ferrous steel industry	E1	Copper slag	Yes	No	No
	E2	Molybdenum slag	No	-	-
	E3	Zinc slag	Yes	No	No
	E4	Phosphorus slag	Yes	No	No
Foundry industry	F1	Foundry sand	Yes	No	No
	F2	Foundry cupola furnace slag	Yes	No	Yes
Mining and quarry industry	G1	Red coal shale	Yes	No	No
	G2	Refuse from hard coal mining (black coal shale)	Yes	No	Yes
	G3	Pre-selected all-in from quarry/mining	Yes	No	No
	G4	Spent oil shale	Yes	No	No
Maintenance dredging works	H1	Dredge spoil sand	Yes	No	No
	H2	Dredge spoil clay	No	-	-
Miscellaneous	I1	Excavated soil	No	-	-
	I2	Paper sludge ash	Yes	No	Yes
	I3	Sewage sludge ash	Yes	No	Yes
	I4	Biomass ash	Yes	No	Yes
	I5	Crushed glass	Yes	Yes	No
	I6	Expanded clay	See EN 13055		

The development of additional criteria may in effect place restrictions of the use of a given material or, alternatively, facilitate improved confidence in that alternative material.

I.9 Relevant standards on sustainability of construction works

The technical committee under CEN (TC 350) has been mandated to develop voluntary horizontal standardized methods for the assessment of the sustainability aspects of new and existing construction works and standards for the environmental product declaration of construction products. The European standardisation approach mandate is based on a lifecycle assessment methodology covering production (mandatory), construction, use (including maintenance) and end of life stages (all optional).

Among the published standards, it is advisable mentioning:

- EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. Other infrastructures are also included in this standard
- EN 15804:2012+A1:2013 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. This standard concerns product categories' rules and frames for developing EPDs

CEN (TC 350) will also consider social and economic aspects of sustainability, but these standards are currently under development.

ISO standards exist for determining life cycle impacts. The interested reader is guided towards EN ISO 14040: 2006, EN ISO 14044: 2006, EN ISO 14025: 2010 and EN ISO 21930:2007 for further details.

I.10 Relevant standards on construction products – Assessment of release of dangerous substances

The technical committee under CEN (TC 351) was established in 2005 under the framework of the Construction Products Directive (89/106/EEC - CPD). It deals with the emission of dangerous substances from construction products that may have harmful impacts on human health and the environment.

Among the standards currently under approval, it is worth mentioning:

- FprCEN/TS 16637-1 Construction products - Assessment of release of dangerous substances - Part 1: Guidance for the determination of leaching tests and additional testing steps
- FprCEN/TS 16637-2 Construction products - Assessment of release of dangerous substances - Part 2: Horizontal dynamic surface leaching test
- prEN 16687 Construction products - Assessment of release of dangerous substances – Terminology

Among the standards currently under drafting:

- CEN/TC 351/WG 1 N 162 Generic horizontal up-flow percolation test for determination of the release of substances from granular construction products

I.11 Relevant standards related to noise management in road construction (and use) in the EU

Legislation and standards regarding noise is split into two distinct categories:

- Noise exposure in places of work (regarding workers and employers).
- Environmental noise (regarding the general public).

During the construction phase, significant noise will be generated by heavy machinery, compaction equipment and the movement of large quantities of raw materials. Noise exposure to workers is generally complied with thanks to the appropriate use of personal protective equipment and is covered by relevant Occupational Health and Safety legislation that is outside the scope of GPP. However, environmental noise levels expected to be generated during construction works should be detailed in the Environmental Impact Assessment (EIA) for the project.

In terms of environmental noise emission, by far the largest impact occurs during the use phase of the road. Noise from engines, tyre-rod contact and air turbulence are the main types of environmental noise produced by traffic.

*"**Directive 2002/49/EC** relating to the assessment and management of environmental noise*", is applicable to noise from roads and requires the development of common assessment methods for environmental noise, mapping of noise impacts in strategic areas and to develop action plans in areas of interest. For monitoring sites, the common noise indicators $\mathbf{L_{den}}$ (day-evening-night) to assess annoyance) and $\mathbf{L_{night}}$ (to assess sleep disturbance) are specified. These are A-weighted long-term average sound levels as defined in ISO 1996-2: 1987. Day is defined as 0700 to 1900, evening as 1900 to 2300 and night as 2300-0700 hours (local time).

Noise maps are required for "*agglomerations*" (urbanised area of population >250,000) and "*major roads*" (more than 6 million vehicle passages per year) and should be reviewed at least every 5 years. Sections of areas around major roads should be classified into different bands based on average sound levels as per the table below.

Indicator	50-54dB	55-59dB	60-64dB	65-69dB	70-74dB	>70dB	>75dB
L_{den}		X	X	X	X		X
L_{night}	X	X	X	X		X	

The main techniques for measuring sound levels are:

- The Statistical Pass-By Method (SPB) ISO 11819-1
- The Controlled Pass-By Method (CPB) – a modified version of the SPB
- The Close-Proximity Method (CPX) ISO/CD 11819-2

Each technique has its own advantages and disadvantages. The SPB provides real data that is directly related to noise levels experienced by pedestrians, but data collection is time consuming since it can only be gathered from single points at a time. Variable vehicle speeds and weather conditions complicate data processing.

The CPB method uses dedicated road sections and test vehicles under controlled conditions to quickly gather data that is simpler to process than with the SPB technique. Although it is difficult to determine what range of test vehicles can adequately represent the range of vehicles found on real roads, this could be a useful potential verification tool for GPP – since before opening the road, it can be used for CPB testing.

Finally, the CPX method consists of a series of microphones attached to a vehicle, placed near a tyre in contact with the road. Unlike SPB and CPB techniques where microphones are at fixed points on the pavement, with CPX the microphone follows the same trajectory as the tyre, producing data along the entire road length of the test run. This type of test could also be of value in verification purposes for GPP criteria, especially where long road lengths are constructed. It could potentially highlight road sections where the surface course deviates from expected acoustic performance. Due to the sheer number of factors that affect noise emissions in public roads, it is impossible to specify that a road shall not produce greater than a certain level of noise. However, this report should focus in some detail on the potential to specify and/or control tyre-road noise emission, which is directly a function of the properties of the road surface course, which **can** be controlled via GPP.

I.12 Standards for drainage performance of roads

Road surfaces are generally impermeable and the sheer scale of road infrastructure means that during rainfall events, they have a significant impact on the natural flow of storm water. Adequate drainage of roads is required because they are not designed to perform their function, which is to permit the safe passage of traffic, while standing water remains on the road surface. Some of the main problems caused by standing water on road surfaces are:

- Water acts as a lubricant and significantly reduces tyre grip on the road surface.
- Spray from water thrown up by tyres reduces driver visibility.
- Water is an incompressible fluid, transmitting the force of vehicle weights directly on the wearing course beneath the water.
- Standing water will freeze to ice in sufficiently cold conditions. This is both a direct hazard to drivers and a risk to the structural integrity of road materials due to subsequent freeze-thaw phenomena.

Historically each country has developed its own standards and minimum requirements with regards to drainage of roads and other developments according to experience. Drainage engineering has evolved in each country and region according to the particular nature of climatic conditions, topography and soil types there. National standards and guidance documentation can be incredibly specialised. An example of some of the main relevant standards for road drainage in the UK is shown in Table _.

Table I.18: A list of UK Highway Authority (HA) standards for road drainage

Number	Title of reference document
HA 78/96	Design of Outfalls for Surface Water Channels
HA 39/98	Edge of Pavement Details
HA 103/06	Vegetative Treatment Systems for Highway Runoff
HA 106/04	Drainage of Runoff from Natural Catchments
TA 80/99	Surface Drainage of Wide Carriageways
HD 33/06	Surface and Sub-surface Drainage Systems for Highways
HA 102/00	Spacing of Road Gullies
HA 105/04	Sumpless Gullies
HA 79/97	Edge of Pavement Details for Porous Asphalt Surface Courses
HA 37/97	Hydraulic Design of Road-Edge Surface Water Channels
HA 83/99	Safety Aspects of Road Edge Drainage Features
HA 43/04	Drainage Data Management System for Highways Agency
HA 217/08	Alternative Filter Media and Surface Stabilisation Techniques for Combined Surface and Sub-Surface Drains
HA 219/09	Determination of Pipe Roughness and Assessment of Sediment Deposition to Aid Pipeline Design
HA 104/09	Chamber Tops and Gully Tops for Road Drainage and Services: Installation and Maintenance
HA 113/05	Combined Channel and Pipe System for Surface Water Drainage
HA 107/04	Design of Outfall and Culvert Details
HA 118/06	Design of Soakaways
HA 119/06	Grassed Surface Water Channels for Highway Runoff

While drainage engineering approaches vary between member states, the "hardware" of drainage infrastructure can involve many different standardised elements which are then assembled together by drainage engineers to create a solution tailored to the proposed construction. Some examples of these elements are listed below.

- **Oil separators** (EN 858) – for use in areas at high risk of fuel spillage such as service stations. These can be either plastic concrete or metallic and the standards these materials have to conform to are further specified in other EN standards.
- **Road culverts** – for enabling water flows (ground or surface water) to pass across the road (underneath) without coming into contact with the road binder courses.
- **Gully tops** – receive the runoff directly from the road surface. Are usually made of iron.
- **Gully sumps** – placed at the bottom of gullies and act as silt traps. Need to be periodically emptied.
- **Manholes** – generally made of pre-fabricated concrete rings.

Road drainage performance is modelled using hydraulic principles and an input-output approach. Roads are designed with minimum cambers to ensure suitable flow velocities of storm water from the road surface to the drains. The drainage infrastructure will be sized in order to be able to remove all storm water from a "design storm event". Minimum requirements are generally specified by the local planning authority and/or environment agency.

At the European level, it can be argued that road drainage falls somewhat within the scope of the Water Framework Directive (2000/60/EC) since pollutants are transferred to watercourses when drains are not combined with mains sewerage systems. Of greater relevance however, is the EU Floods Directive (2007/60/EC). Under the requirements of the EU Floods Directive, member states had to undertake a preliminary flood risk assessment in all river basins and coastal zones by 2011 and develop flood hazard maps and flood risk maps for areas of concern by 2013. GPP specified road drainage has the potential to play a crucial role in flood risk management in areas of concern, which will be mentioned in more detail later in the report.

Table I.19: Summary of EN 450-1 requirements for coal fly ash in EN 206 concrete

Criteria	Standard	Requirement / Comments
Loss on ignition	EN 196-2	<5.0% (Cat. A), <7.0% (Cat. B) or < 9.0% (Cat. C)
Chloride	EN 196-2	≤0.10% by mass
Sulfate	EN 196-2	≤3.0% by mass
Free CaO	EN 451-1	If >1.5%, an additional soundness test is required.
Reactive CaO	EN 197-1	≤10.0% by mass
Reactive SiO_2	EN 197-1	≤25.0% by mass (for co-combustion ashes only)
$SiO_2 + Al_2O_3 + Fe_2O_3$	≥70%	
Total Alkali content	EN 196-2	
Magnesium oxide	EN 196-2	≤4.0% by mass
Phosphate	ISO 29851-2	≤5.0% by mass
Fineness	EN 451-2 or EN 933-10	<40% >45µm (Cat. N), or <12% >45 µm (Cat. S)
Activity index	EN 196-1	>75% of control strength at 28d and >85% after 90d.
Soundness	EN 196-3	<10mm expansion on samples of FA/CEM = 30/70
Particle density	EN 1097-7	Within 200kg/m^3 of value specified by client
Initial setting time	EN 196-3	Not be >2x longer than control for a 25/75 mixture. Also will comply with other criteria in EN 197-1.
Water requirement	EN 1015-3	Declare a quantity of water required to provide the same "flowability" (+/-10mm) as control mortar with 225g water.

Table I.20: Summary of EN 15167-1 requirements for blast furnace slag in EN 206 concrete.

Criteria	Standard	Requirement / Comments
Elemental composition	-	CaO + MgO + SiO_2 shall account for at least two thirds of sample dry mass (when all elements present are expressed as oxides).
Grinding aid impurities	-	<1.0% content of slag and organic impurities from aids shall not exceed 0.2% of slag mass.
Magnesium oxide	EN 196-2	≤ 18%
Sulfide	EN 196-2	≤ 2.0%
Sulfate	EN 196-2	≤ 2.5%
Loss on ignition	EN 196-2	≤ 3.0% - corrected for sulphide oxidation
Chloride	EN 196-2	≤ 0.10%
Moisture content	EN 15167-1 Annex A	≤ 1.0%
Fineness	EN 196-6	≥275m^2/g air permeability method
Initial setting time	EN 196-3	A blended cement (50% slag + 50% cement) shall set in less than double the time as a control reference containing 100% cement.
Activity index	EN 196-1	A blended cement (50% slag + 50% cement) shall develop at least 45% of 7d comp. strength and 70% of 28d comp. strength as the reference cement.

I.13 Standards: Stakeholder feedback

Table I.21: Test standards (noise, rolling resistance etc.)

There is a total legal standards for noise, including measurement, calculation methods et cetera. Rolling resistance is not measured. IRI is (NL)
No standards yet but to be developed in the coming EU FP7 project Rosanne (ROlling resistance, Skid resistance, ANd Noise Emission measurement standards for road surfaces) (DK)
Noise (IT) D.M. Ambiente 16 Marzo 1998 – Evaluation and measure techniques of acoustic pollution from road traffic_Annex C. (measures "in situ"). There are not relevant legislation that prescribe test methods in relationship to noise. References are usually to European standard. On the contrary there are evaluation model of acoustic level based on regression formula that takes into account one or more of parameters responsible for noise (vehicles and traffic volume, aerodynamic of vehicles, geometric/structural properties of roads such as texture and porosity of surface, number of lanes breadth of road, incline level %, geometric section): - simplified model (take into account traffic hourly data and vehicles average speed) - CNR model (take into account traffic and vehicles data, geometric/structural data of road, context data), - SEL model – single event model (takes into account five transport class and two road type). *Rolling resistance* There are not relevant legislation that prescribe test methods and minimum performance levels of road surface in relationship to rolling resistance; References are usually to European standard. Test methods and minimum performance levels in relationship to rolling resistance are specified from the point of view of tyre performance.
Technical specifications for road construction refer to existing European standards to assess the different relevant characteristics
EN ISO 11819-1:2001: Acoustics - Measurement of the influence of road surfaces on traffic noise - Part 1: Statistical Pass-By method (ISO 11819-1:1997)
EN 13863, ISO/DIS 11819-2, ISO 18164

Table I.22: Other relevant standards

(UK) National technical documents for highway construction and maintenance. The Quality Protocol for the Production of Aggregates from Inert Waste - http://aggregain.wrap.org.uk/document.rm?id=87 Construction code of practice for the sustainable use of soils on construction sites - https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69308/pb13298-code-of-practice-090910.pdf Institution of Civil Engineers Demolition Protocol 2008 - http://www.ice.org.uk/getattachment/eb09d18a-cb12-4a27-a54a-651ec31705f1/Demolition-Protocol-2008.aspx
(BE) The certification of recycled granulates is incorporated in the so-called 'unity regulation': this aims to certify the origin and the quality of recycled aggregates through a system of self-assessment and external control. This scheme incorporated the end- of waste criteria for aggregates for their use in and as building materials. Only aggregates with this certification can be applied in the foundations and other layers of constructed roads

ANNEX II. MARKET ANALYSIS

II.1 Market data

Table II.1: Economic indicators for EU-28 and Member States in 2011 and 2012 (Eurostat, 2013a)

	%GDP* 2011	%GDP* 2012	Inflation rate 2011	Inflation rate 2012	Unemployment rate 2012-2013°
EU-28	1.6	-0.4	3.1	2.6	10.9
Belgium	1.8	-0.1	3.4	2.6	8.4
Bulgaria	1.8	0.8	3.4	2.4	12.9
Czech Republic	1.8	-1	2.1	3.5	7.1
Denmark	1.1	-0.4	2.7	2.4	7.1
Germany	3.3	0.7	2.5	2.1	5.4
Estonia	9.6	3.9	5.1	4.2	8.9
Ireland	2.2	0.2	1.2	1.9	13.6
Greece	-7.1	-6.4	3.1	1	26.9
Spain	0.1	-1.6	3.1	2.4	26.4
France	2	0	2.3	2.2	10.8
Croatia	0	-2	2.2	3.4	17.1
Italy	0.5	-2.5	2.9	3.3	11.9
Cyprus	0.4	-2.4	3.5	3.1	15.1
Latvia	5.3	5.2	4.2	2.3	12.6
Lithuania	6	3.7	4.1	3.2	12.2
Luxembourg	1.9	-0.2	3.7	2.9	5.6
Hungary	1.6	-1.7	3.9	5.7	10.6
Malta	1.7	0.9	2.5	3.2	6.5
The Netherlands	0.9	-1.2	2.5	2.8	6.4
Austria	2.8	0.9	3.6	2.6	4.8
Poland	4.5	1.9	3.9	3.7	10.4
Portugal	-1.3	-3.2	3.6	2.8	16.9
Romania	2.2	0.7	5.8	3.4	7.1
Slovenia	0.7	-2.5	2.1	2.8	10.2
Slovakia	3	1.8	4.1	3.7	14.2
Finland	2.7	-0.8	3.3	3.2	8.1
Sweden	2.9	0.9	1.4	0.9	8.1
United Kingdom	1.1	0.1	4.5	2.8	7.7

* Growth percentage from previous year

° Starting from the beginning of November 2012 to the end of October 2013

Table II.2: Production value for the construction sector in EU-28 from 2008 to 2011 (Eurostat, 2013b)

Millions of Euro	**2008**	**2009**	**2010**	**2011**	**Trend 2010-11 (%)**
EU-28	n/a	n/a	n/a	1,555,007	n/a
EU-27	1,935,296	1,592,414	1,566,513	1,543,661	-1.5
Belgium	46,000	49,160	85,261	58,122	-31.8
Bulgaria	11,035	9,866	6,775	6,554	-3.3
Czech Republic	35,218	30,490	30,987	30,667	-1.0
Denmark	32,651	25,645	22,982	26,178	13.9
Germany	174,182	167,641	173,472	197,709	14.0
Estonia	2,900	1,924	1,677	2,241	33.7
Ireland	31,447	23,795	8,759	8,501	-2.9
Greece	n/a	15,656	n/a	n/a	n/a
Spain	368,267	271,777	198,417	156,058	-21.3
France	272,024	247,284	254,942	272,497	6.9
Croatia	11,167	9,528	6,945	6,062	-12.7
Italy	296,984	206,943	227,625	215,455	-5.3
Cyprus	4,304	3,376	3,187	2,834	-11.1
Latvia	5,993	3,289	2,712	3,170	16.9
Lithuania	6,232	2,712	2,740	3,436	25.4
Luxembourg	4,181	4,050	4,003	4,123	3.0
Hungary	9,694	7,903	7,371	6,982	-5.3
Malta	n/a	n/a	n/a	n/a	n/a
The Netherlands	99,065	97,179	83,894	88,944	6.0
Austria	40,935	39,374	38,790	40,267	3.8
Poland	53,988	46,629	50,415	57,351	13.8
Portugal	35,462	32,523	32,422	27,879	-14.0
Romania	26,087	18,721	18,067	19,087	5.7
Slovenia	8,210	6,640	5,670	4,856	-14.4
Slovakia	7,485	6,345	8,483	8,372	-1.3
Finland	27,181	23,875	24,372	27,258	11.8
Sweden	47,198	40,713	48,257	56,099	16.3
United Kingdom	279,755	208,131	208,807	212,959	2.0

Table II.3: Number of employees in the construction sector in EU-28 from 2008 to 2011 (Eurostat, 2013b)

Number	2008	2009	2010	2011	Trend 2010-11 (%)
EU-28	n/a	n/a	n/a	10,214,967	n/a
EU-27	11,473,374	10,960,528	10,361,669	10,107,972	-2.4
Belgium	214,571	214,784	213,938	219,331	2.5
Bulgaria	245,404	222,351	169,254	149,360	-11.8
Czech Republic	271,342	263,441	259,130	242,810	-6.3
Denmark	195,469	138,907	132,148	n/a	n/a
Germany	1,370,549	1,378,035	1,427,477	1,584,664	11.0
Estonia	55,917	42,419	37,190	40,650	9.3
Ireland	98,868	71,848	45,510	56,685	24.6
Greece	n/a	153,935	n/a	n/a	n/a
Spain	1,796,717	1,433,657	1,263,937	1,023,602	-19.0
France	1,306,731	1,525,506	1,563,655	1,531,120	-2.1
Croatia	145,483	139,875	120,361	106,995	-11.1
Italy	1,177,242	1,172,433	1,081,264	998,361	-7.7
Cyprus	37,239	34,289	33,159	31,575	-4.8
Latvia	88,517	57,922	51,556	50,531	-2.0
Lithuania	124,886	89,127	78,779	84,759	7.6
Luxembourg	39,031	39,325	39,005	40,059	2.7
Hungary	204,256	181,269	173,674	164,429	-5.3
Malta	n/a	n/a	n/a	n/a	n/a
The Netherlands	395,983	387,917	373,363	367,057	-1.7
Austria	254,011	252,552	252,056	256,146	1.6
Poland	671,338	685,061	650,058	668,592	2.9
Portugal	489,053	447,721	383,584	345,051	-10.0
Romania	554,399	469,182	393,339	418,202	6.3
Slovenia	76,566	73,636	65,044	56,325	-13.4
Slovakia	83,645	78,118	88,460	80,496	-9.0
Finland	154,236	148,818	150,057	156,595	4.4
Sweden	256,109	252,984	266,616	282,745	6.0

Table II.4: Trend in number of enterprises in the road and motorways construction sector in EU-28 from 2008 to 2011 (Eurostat 2013b)

Number of enterprises	**2008**	**2009**	**2010**	**2011**	**Trend 2010-11 (%)**
EU-28	n/a	n/a	n/a	33,186	n/a
EU-27	29,574	30,129	31,171	32,953	5.7
Belgium	1,242	1,153	1,183	1,367	15.6
Bulgaria	492	513	514	515	0.2
Czech Republic	n/a	n/a	n/a	n/a	n/a
Denmark	n/a	n/a	n/a	n/a	n/a
Germany	2,537	2,801	2,813	2,686	-4.5
Estonia	152	179	188	185	-1.6
Ireland	907	904	562	n/a	n/a
Greece	n/a	2,426	n/a	n/a	n/a
Spain	1,626	1,190	803	967	20.4
France	n/a	1,098	1,033	997	-3.5
Croatia	210	217	228	233	2.2
Italy	3,338	3,467	3,631	4,095	12.8
Cyprus	84	81	69	71	2.9
Latvia	249	235	244	228	-6.6
Lithuania	104	97	96	101	5.2
Luxembourg	44	44	43	43	0.0
Hungary	1,177	1,210	1,224	1,212	-1.0
Malta	n/a	n/a	n/a	n/a	n/a
The Netherlands	3,983	4,322	4,784	4,873	1.9
Austria	466	439	407	341	-16.2
Poland	3,714	3,819	4,919	6,563	33.4
Portugal	323	375	399	397	-0.5
Romania	1,173	1,369	1,369	1,349	-1.5
Slovenia	169	184	181	184	1.7
Slovakia	73	86	131	138	5.3
Finland	255	229	239	271	13.4
Sweden	449	465	492	520	5.7
United Kingdom	2,677	2,650	2,528	2,439	-3.5

Table II.5: Turnover or gross premiums written in the roads and motorways construction sector in EU-28 from 2008 to 2011 (Eurostat, 2013b)

Millions of Euro	2008	2009	2010	2011	Trend 2010-11 (%)
EU-28	n/a	n/a	n/a	108,050	n/a
EU-27	113,718	106,597	101,354	106,946*	5.5
Belgium	4,259	4,476	3,088	3,405	10.3
Bulgaria	1,101	959	990	1,225	23.8
Czech Republic	n/a	n/a	n/a	n/a	n/a
Denmark	n/a	n/a	n/a	n/a	n/a
Germany	11,246	11,795	10,906	12,798	17.4
Estonia	450	363	307	333	8.5
Ireland	1,427	1,332	568	n/a	n/a
Greece	n/a	1,894	n/a	n/a	n/a
Spain	17,488	15,001	10,777	9,421	-12.6
France	n/a	15,199	15,036	16,546	10.0
Croatia	1,418	1,427	1,319	1,104	-16.3
Italy	10,456	9,244	10,419	10,708	2.8
Cyprus	519	354	360	366	1.7
Latvia	738	327	351	468	33.1
Lithuania	742	403	454	512	12.6
Luxembourg	n/a	n/a	n/a	588	n/a
Hungary	2,271	2,814	1,608	1,480	-7.9
Malta	n/a	n/a	n/a	n/a	n/a
The Netherlands	n/a	n/a	n/a	n/a	n/a
Austria	5,176	4,624	5,411	4,190	-22.6
Poland	5,819	5,640	7,134	9,596	34.5
Portugal	3,594	4,159	4,821	4,992	3.6
Romania	4,396	3,607	3,273	3,621	10.6
Slovenia	1,682	1,374	1,077	772	-28.3
Slovakia	1,555	1,514	1,223	1,503	22.9
Finland	1,835	1,533	1,517	1,673	10.3
Sweden	1,234	1,329	1,685	2,180	29.4
United Kingdom	6,151	5,249	5,417	6,236	15.1

* data EU-28 – data Croatia

Table II.6: Production value in the roads and motorways construction sector from 2008 to 2011 in EU-28 (Eurostat, 2013b)

Millions of Euro	2008	2009	2010	2011	Trend 2010-11 (%)
EU-28	n/a	n/a	n/a	108,785	n/a
EU-27	112,534	106,089	100,829	107,631	6.7
Belgium	4,542	4,739	2,916	3,185	9.2
Bulgaria	1,122	985	1,063	1,269	19.4
Czech Republic	n/a	n/a	n/a	n/a	n/a
Denmark	n/a	n/a	n/a	n/a	n/a
Germany	11,357	11,824	11,418	12,968	13.6
Estonia	350	274	221	257	16.6
Ireland	1,439	1,422	526	n/a	n/a
Greece	n/a	1,940	n/a	n/a	n/a
Spain	18,057	15,426	10,954	9,686	-11.6
France	n/a	14,993	14,996	16,515	10.1
Croatia	1,483	1,467	1,349	1,155	-14.4
Italy	9,842	9,485	11,326	12,531	10.6
Cyprus	520	357	361	366	1.6
Latvia	747	328	358	477	33.1
Lithuania	747	409	453	511	12.9
Luxembourg	n/a	n/a	n/a	471	n/a
Hungary	1,132	1,297	959	783	-18.4
Malta	n/a	n/a	n/a	n/a	n/a
The Netherlands	n/a	n/a	n/a	n/a	n/a
Austria	5,495	5,207	4,520	4,623	2.3
Poland	4,641	4,664	5,874	8,025	36.6
Portugal	3,776	4,385	5,142	5,220	1.5
Romania	5,217	4,009	3,797	4,234	11.5
Slovenia	1,582	1,344	1,005	742	-26.2
Slovakia	1,548	1,488	1,207	1,466	21.4
Finland	1,849	1,513	1,523	1,687	10.8
Sweden	1,217	1,727	1,662	2,136	28.5
United Kingdom	6,159	5,209	5,414	6,184	14.2

Table II.7: Trend in gross investment in machinery and equipment in the roads and motorways construction sector from 2008 to 2011 in EU-28 (Eurostat, 2013b)

Millions of Euro	2008	2009	2010	2011	Trend 2010-11 (%)
EU-28	n/a	n/a	n/a	n/a	n/a
EU-27	n/a	n/a	n/a	n/a	n/a
Belgium	9,511	1,354	111	166	49.7
Bulgaria	104	47	34	42	24.1
Czech Republic	n/a	n/a	n/a	n/a	n/a
Denmark	n/a	n/a	n/a	n/a	n/a
Germany	357	332	349	442	26.7
Estonia	30	11	12	14	17.9
Ireland	17	6	2	n/a	n/a
Greece	:	32	n/a	n/a	n/a
Spain	293	154	116	85	-26.6
France	n/a	n/a	n/a	n/a	n/a
Croatia	77	40	28	35	26.5
Italy	390	408	433	171	-60.5
Cyprus	24	11	8	4	-49.4
Latvia	n/a	n/a	n/a	n/a	n/a
Lithuania	39	8	12	15	25.6
Luxembourg	n/a	n/a	n/a	8	n/a
Hungary	97	34	32	20	-35.6
Malta	n/a	n/a	n/a	n/a	n/a
The Netherlands	n/a	n/a	197	209	n/a
Austria	68	49	60	88	47.2
Poland	226	189	265	260	-2.0
Portugal	185	151	78	79	1.8
Romania	381	191	218	399	82.9
Slovenia	39	n/a	n/a	n/a	n/a
Slovakia	42	16	20	7	-65.8
Finland	236	33	34	49	43.1
Sweden	52	32	57	57	-0.2
United Kingdom	131	52	105	78	-25.6

Table II.8: Number of employees in the roads and motorways construction sector in EU-28 from 2008 to 2011 (Eurostat, 2013b)

Number	2008	2009	2010	2011	Trend 2010-11 (%)
EU-28	n/a	n/a	n/a	635,900	n/a
EU-27	651,400	646,100	621,500	621,582	0.0
Belgium	14,922	15,043	14,801	14,005	-5.4
Bulgaria	22,236	20,988	19,545	18,773	-3.9
Czech Republic	n/a	n/a	n/a	n/a	n/a
Denmark	n/a	n/a	n/a	n/a	n/a
Germany	75,267	77,760	79,230	81,271	2.6
Estonia	4,218	3,910	3,370	3,107	-7.8
Ireland	3,748	2,404	1,339	n/a	n/a
Greece	n/a	14,859	n/a	n/a	n/a
Spain	82,795	69,593	51,860	46,743	-9.9
France	n/a	83,177	80,586	82,213	2.0
Croatia	15,228	16,834	15,630	14,318	-8.4
Italy	36,191	40,242	43,098	42,019	-2.5
Cyprus	5,469	4,851	4,530	4,145	-8.5
Latvia	8,597	6,647	5,757	5,856	1.7
Lithuania	9,942	7,950	7,429	7,621	2.6
Luxembourg	n/a	n/a	n/a	4,060	n/a
Hungary	11,466	12,510	11,849	10,221	-13.7
Malta	n/a	n/a	n/a	n/a	n/a
The Netherlands	28,257	28,497	28,582	27,624	-3.4
Austria	18,811	18,335	17,909	17,874	-0.2
Poland	56,615	62,828	68,126	78,182	14.8
Portugal	27,348	28,846	26,795	20,796	-22.4
Romania	59,599	54,480	48,198	51,802	7.5
Slovenia	8,756	7,926	7,301	6,167	-15.5
Slovakia	10,854	10,659	10,666	8,661	-18.8
Finland	6,753	6,853	6,284	6,103	-2.9
Sweden	4,659	7,208	7,505	7,474	-0.4
United Kingdom	30,699	n/a	n/a	n/a	n/a

Table II.9: Production of different typologies of aggregates for 2010 in EU-27, 34 Countries and EFTA Countries (UEPG, 2012)

Member State	Total number of producers	Total number of extraction sites	Sand gravel (Mt)	Crushed rock (Mt)	Marine aggregates (Mt)	Recycled aggregates (Mt)	Manufactured aggregates (Mt)	Total Production (Mt)
Austria	1070	1362	61	31	0	4	2	97
Belgium	84	112	14	44	8	15	1	82
Bulgaria	190	280	11	14	0	0	0	24
Croatia	175	299	4	14	0	0	0	18
Cyprus	24	24	0	13	0	0	0	13
Czech Rep	202	378	19	37	0	0	0	56
Denmark	350	392	30	0	9	1	8	49
Estonia	31	291	7	0	0	0	0	7
Finland	400	2031	36	48	0	1	0	85
France	1347	2468	135	201	6	17	6	365
Germany	1400	2100	239	208	9	60	19	535
Greece	171	186	1	47	0	0	0	48
Hungary	305	589	30	18	0	3	0	51
Iceland	28	56	2	1	1	0	0	3
Ireland	130	500	10	40	0	0	0	50
Italy	1470	2200	180	120	0	0	0	300
Latvia	30	352	6	3	0	0	0	9
Lithuania	30	427	11	3	0	0	0	14
Luxembourg	7	10	1	1	0	0	0	2
Malta	15	16	1	0	0	0	0	1
Netherlands	145	250	40	0	17	20	0	76
Norway	726	1043	13	54	0	0	0	67
Poland	1542	2475	163	77	0	9	3	252
Portugal	288	362	8	59	0	0	0	67
Romania	430	735	34	15	0	0	0	49
Russia	1181	1485	163	234	0	0	25	422
Serbia	20	70	12	8	0	0	0	19
Slovakia	185	299	8	18	0	0	0	26
Slovenia	30	50	5	8	0	0	0	13
Spain	1475	1520	52	155	0	0	0	208
Sweden	985	1575	17	57	0	1	6	81
Switzerland	537	530	40	5	0	5	0	51
Turkey	770	770	25	290	0	0	0	315
UK	885	1393	51	106	10	49	10	226
34 Countries	**16658**	**26630**	**1426**	**1929**	**59**	**186**	**80**	**3680**
Like-for-Like	15306	23943	1230	1680	58	185	55	3209
EU-27 +EFTA	14512	24006	1223	1383	59	186	55	2906
EU-27	**13221**	**22377**	**1168**	**1323**	**58**	**180**	**55**	**2784**

The EFTA countries include Iceland, Norway and Switzerland

Table II.10: Production, import and export data for construction sand (PRODCOM 08.12.11.90) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	2009	2010	2011	2012
Produced quantity (Mt)	392	425	429	380
Produced value (M€)	3,290	3,050	2,888	2,888
Import quantity (Mt)	31	30	32	30
Import value (M€)	283	277	269	311
Export quantity (Mt)	22	22	24	20
Export value (M€)	221	182	238	237

Table II.11: Production, import and export data for gravels and pebbles (PRODCOM 08.12.12.10) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	2009	2010	2011	2012
Produced quantity (Mt)	544	510	522	472
Produced value (M€)	4,140	4,020	3,960	3,760
Import quantity (Mt)	32	23	24	27
Import value (M€)	375	343	292	326
Export quantity (Mt)	36	33	33	31
Export value (M€)	355	285	346	325

Table II.12: Production, import and export data for crushed stones (PRODCOM 08.12.12.30) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	2009	2010	2011	2012
Produced quantity (Mt)	822	980	902	808
Produced value (M€)	6,230	6,120	5,800	5,280
Import quantity (Mt)	14	19	19	14
Import value (M€)	170	215	222	178
Export quantity (Mt)	9	11	13	9
Export value (M€)	93	97	150	112

Table II.13: Production, import and export data for pre-coated aggregates (PRODCOM 23.99.13.20) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	2009	2010	2011	2012
Produced quantity (Mt)	29	25	25	21
Produced value (M€)	1,211	1,052	1,208	1,078
Import quantity (Mt)	0	0	1	0
Import value (M€)	16	18	21	21
Export quantity (Mt)	0.4	0.4	0.7	0.4
Export value (M€)	21	25	36	34

Table II.14: Production, import and export data for silica sand (PRODCOM 08.12.11.50) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	**2009**	**2010**	**2011**	**2012**
Produced quantity (Mt)	69	72	77	71
Produced value (M€)	865	923	934	866
Import quantity (Mt)	1.6	1.8	2.1	2.1
Import value (M€)	0	0	0	0
Export quantity (Mt)	8	8	8	7
Export value (M€)	204	231	259	243

Table II.15: Production, import and export data for natural bitumen and asphalt (PRODCOM 08.99.10.00) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	**2009**	**2010**	**2011**	**2012**
Produced quantity (Mt)	2.0	2.9	2.7	1.9
Produced value (M€)	85	140	120	106
Import quantity (Mt)	0.7	1.0	0.7	0.6
Import value (M€)	115	132	180	112
Export quantity (Mt)	0.5	0.5	0.4	0.3
Export value (M€)	75	76	95	72

Table II.16: Production data of hot mix asphalt (HMA) and warm mix asphalt (WMA) in EU-27 from 2006 to 2011 (EAPA, 2012)

Country	2006	2007	2008	2009	2010	2011
	(Mt)	(Mt)	(Mt)	(Mt)	(Mt)	(Mt)
EU-27	**346.1**	**347.7**	**338**	**317.3**	**309.3**	**324.3**
Austria	10	9.5	9.5	9	8.2	8
Belgium	5	4.5	4.9	4.7	4.8	5.9
Croatia	3.7	3.7	4.2	3.2	2.7	2.6
Czech Republic	7.4	7	7.3	7	6.2	5.8
Denmark	3.4	3.3	3.1	2.7	3.2	4
Estonia	1.5	1.5	1.5	1.2	1.1	1.3
Finland	5.5	5.9	6	5.2	4.9	5
France	41.5	42.3	41.8	40.1	38.8	39.2
Germany	57	51	51	55	45	50
Great Britain	25.7	25.7	25	20.5	21.5	22.4
Greece	7.8	8	8.1	8.7	5.2	2.3
Hungary	4.4	3.3	2.5	1.6	3.4	2.3
Ireland	3.5	3.3	2.8	3.3	2.3	1.8
Italy	44.3	39.9	36.5	34.9	29	28
Latvia	0.6	0.6	0.6	0.6	0.6	0.6
Lithuania	1.7	2.2	1.5	1.6	1.6	
Luxembourg	0.6	0.6	0.6	0.6	0.7	0.7
Netherlands	9.8	10.2	9.3	9.8	9.5	9.6
Poland	18	18	15	18	18	26.5
Portugal	8.9	9	9	9	6.7	6.4
Romania	2.8	3.2	3.3	3.6	3.2	3.6
Slovakia	2.2	2.2	2.2	2.2	1.9	2.2
Slovenia	2.2	2.1	2.6	2.3	1.8	1.3
Spain	43.4	49.9	42.3	39	34.4	29.3
Sweden	7.3	7.7	8.7	8.1	7.9	8.1

Table II.17: Production, import and export data for bituminous mixtures (PRODCOM 23.99.13.10) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	**2009**	**2010**	**2011**	**2012**
Produced quantity (Mt)	200	82	90	79
Produced value (M€)	4,360	4,520	5,180	5,000
Import quantity (Mt)	0.7	0.7	0.7	0.6
Import value (M€)	195	244	283	258
Export quantity (Mt)	0.8	0.7	0.8	0.7
Export value (M€)	183	203	256	300

Table II.18: Production of reclaimed asphalt pavement RAP in Europe (EAPA, 2012)

Country	**RAP**	**% Available reclaimed asphalt used in**				**% of the new HMA and WMA production that reclaimed materials**
	(Mt)	**hot and warm recycling**	**half warm recycling**	**cold recycling**	**unbound layers**	
Austria	0.6	90	5	5		
Belgium	1.5	65	50			50
Czech Republic	1.5	14	0	35	15	10
Denmark	0.6	80	20	53		53
Finland	1.0	65				65
France	7.1	45	>30			<30
Germany	14.0	84	16	65		65
Greece	0.0	0	0	0	0	0.01
UK	4.5					
Hungary	0.1	100	0	0	0	30
Ireland	0.1	40	0	0	2	2
Italy	11.0	20				
Luxembourg	0.2	95	0	5	80	80
Netherlands	4.0	83	15	71		71
Poland	0.1	~4	0.2			0.2
Portugal	0.0	60	0	5	15	20
Romania	0.0	60	12	15	5	<8
Slovenia	0.0	30	20	50		
Spain	1.4	73	10	17		
Sweden	1.1	70	5	5	15	65
EUROPA	**49**					

Table II.19: Production, import and export data for Portland Cement (PRODCOM 23.51.12.10) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	**2009**	**2010**	**2011**	**2012**
Produced quantity (Mt)	171	163	163	146
Produced value (M€)	12,690	11,538	11,590	10,767
Import quantity (Mt)	12	13	14	13
Import value (M€)	828	857	942	831
Export quantity (Mt)	18	21	22	24
Export value (M€)	1,139	1,237	1,352	1,457

Table II.20: Production, import and export data for "other" hydraulic cement (PRODCOM 23.51.12.90) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	2009	2010	2011	2012
Produced quantity (Mt)	30	25	31	30
Produced value (M€)	2,319	1,931	2,274	2,376
Import quantity (Mt)	n/a	1.9	1.9	1.6
Import value (M€)	n/a	160	152	22
Export quantity (Mt)	n/a	3.4	3.5	2.8
Export value (M€)	n/a	257	255	230

Table II.21: Production, import and export data for ready mixed concrete (PRODCOM 23.63.10.10) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	2009	2010	2011	2012
Produced quantity (Mt)	696	585	507	556
Produced value (M€)	19,890	18,058	18,489	18,078
Import quantity (Mt)	1.3	1.4	1.4	1.2
Import value (M€)	261	277	305	287
Export quantity (Mt)	1.8	1.8	1.9	1.8
Export value (M€)	402	433	490	489

Table II.22: C&D waste arising and recycling rates in the EU-27 (BIOIS, 2011)

Country	C&D waste arising	C&D waste arising	% Re-used or recycled
	(Mt)	(tonnes/capita)	
Austria	6.60	0.81	60%
Belgium	11.02	1.06	68%
Bulgaria	7.80	0.39	n.a.
Cyprus	0.73	0.58	1%
Czech Republic	14.70	1.44	23%
Denmark	5.27	3.99	94%
Estonia	1.51	1.12	92%
Finland	5.21	3.99	26%
France	85.65*	5.50	45%
Germany	72.40	2.33	86%
Greece	11.04	0.37	5%
Hungary	10.12	0.43	16%
Ireland	2.54	2.74	80%
Italy	46.31	0.80	n.a.
Latvia	2.32	0.04	46%
Lithuania	3.45	0.10	60%
Luxembourg	0.67	5.90	46%
Malta	0.8	1.95	n.a.
Netherlands	23.9	1.47	98%
Poland	38.19	0.11	28%
Portugal	11.42	1.09	5%
Romania	21.71	n.a.	n.a.
Slovakia	5.38	0.26	n.a.
Slovenia	2.00	n.a.	53%
Spain	31.34	0.74	14%
Sweden	10.23	1.14	n.a.
United Kingdom	99.10*	1.66	75%
EU 27	**531.38**	**1.74**	**46%**

* corrected with the exclusion of excavated materials

Table II.23: Coal combustion residues in Europe in 2004 (Umweltesbundesamt, 2008 - based on ECOBA)

(Mt/year)	Fly ash	Bottom ash	Boiler slag	Flue gas desulphurisation gypsum	Spray dry absorption residue	Total	Percentage	Year
Germany	13.88	2.28	1.95	7.66	0.28	26.05	29	2004
Poland	13.52	2.35	0.81	2.63	0.06	19.36	22	2001
Greece	11.39	0.66	0.00	0.29	0.00	12.34	14	2004
Spain	6.51	1.28	0.00	0.90	0.00	8.68	10	2004
Romania	7.16	1.38	0.00	0.00	0.00	8.54	10	2002
UK	6.51	0.81	0.00	1.05	0.00	8.37	9	2004
Bulgaria	4.47	0.83	0.00	0.62	0.00	5.91	7	2003
Hungary	2.72	0.51	0.00	0.38	0.00	3.61	4	2000
Slovak Republic	2.09	0.33	0.00	0.31	0.19	2.92	3	1998
Czech Republic	1.50	0.67	0.23	0.33	0.01	2.73	3	2005
Slovenia	1.34	0.03	0.00	0.38	0.00	1.76	2	2002
Italy	1.13	0.13	0.00	0.36	0.00	1.62	2	2004
France	1.34	0.14	0.00	0.07	0.00	1.55	2	2004
Netherlands	1.02	0.18	0.00	0.31	0.00	1.51	2	2004
Denmark	0.73	0.10	0.00	0.26	0.06	1.15	1	2004
Finland	0.54	0.09	0.00	0.07	0.03	0.73	1	2004
Portugal	0.54	0.05	0.00	0.00	0.00	0.59	1	2004
Belgium	0.40	0.06	0.00	0.06	0.00	0.51	1	2004
Austria	0.35	0.04	0.00	0.05	0.06	0.50	1	2004
Ireland	0.18	0.02	0.00	0.00	0.00	0.20	0	2004
Latvia	0.02	0.00	0.00	0.00	0.00	0.02	0	2003
Luxembourg	0	0	0	0	0	0	0	2004
Sweden	0	0	0	0	0	0	0	2004
Malta	0	0	0	0	0	0	0	2003
Estonia	—	—	—	—	—	—	—	—
Lithuania	—	—	—	—	—	—	—	—
Cyprus	—	—	—	—	—	—	—	—
EUROPE	**77.33**	**11.93**	**2.99**	**15.72**	**0.68**	**108.65**	**1.21**	

Table II.24: Production, import and export data for reclaimed rubber (PRODCOM 22.19.10.00) in EU-28 from 2009 to 2012 (Eurostat, 2013a)

EU-28	**2009**	**2010**	**2011**	**2012**
Produced quantity (Mt)	0.3	0.1	0.6	0.5
Produced value (M€)	70	88	128	145
Import quantity (Mt)	0.0	0.1	0.1	0.0
Import value (M€)	34	45	46	48
Export quantity (Mt)	0.1	0.1	0.1	0.1
Export value (M€)	50	57	48	53

II.2 Stakeholders feedback on market analysis

Table II.25: Stakeholders feedbacks on road constructed and maintained nationally per year for the last three years (2010-11-12)

- 2010 Constructed 120 lane kms - 2011 Constructed circa 50 lane kms - 2012 Constructed a little over 400 lane kms The road network is inspected regularly to enable maintenance to be planned on a priority basis and ensure the safety of the road user. All planned non-routine road renewals maintenance expenditure is capitalised as it is recognised the maintenance spend enhances or replaces the service potential of the road network. Maintenance is circa 1,500 lane kms/year (UK)
The main motorway network of RWS consists of about 3000 km motorway, (2 and more lanes) Approximately 10 % is being resurfaced avery year (NL)
2012: 81 Data refer to *construction site* for construction of *highways and roads of national interest* (up-to-date to 12th april 2013): actually, 81 km of roads are in construction (work in progress – source: ANAS) (IT)
2010 – 1270 km/year (2010) - 1111 km/year (2011) - 1371 km/year (2012) (turkey)

Table II.26: Stakeholders feedbacks on future constructed road km in 2014 and 2020

When complete schemes starting in 2013-14 will add an additional 240 lane kms (UK)

Table II.27: Stakeholders feedbacks on materials for construction in general and for road construction

	UK	NL	DK	IT	IT Trento province	BE	IND ASS	IND ASS	IND ASS	IND ASS	IND ASS	IND ASS
			average 2007-12	av. 2008-10	av. 2007-09		EU level	EU level	EU level	EU level	EU level	EU level
Material	[kt/y] In the construction sector	[kt/y] In the construction sector	[kt/y] In the construction sector	[kt/y] In the construction sector	[kt/y] In the construction sector	[kt/y] In the construction sector	[kt/y] In the construction sector	[kt/y] In the road sector	[kt/y] In the construction sector	[kt/y] In the road sector	[kt/y] In the construction sector	[kt/y] In the road sector
Natural aggregates	1,913	130,000		340,000	1,793							
By-products	0	5,000		3,000	included in natural						37,400	16,600
Recycled aggregates	1,094	25,000		5,000	1,149	11,000						
Secondary aggregates	0	0		0								
Bitumen	44	400		1,475								
Asphalt	1,178	8,000	1,100	28,300	746.786 (10% recycled)		300,000	300,000				
Cement	32			32,000								
Concrete	496			20,300	1813.796 (2% recycled)							
Lime or other binders	0			19000 (15% pre cast)					3,760	400		
Salt for winter maintenance	261	100	70									
Waste derived materials	0	0										
Other materials	536	1										

Table II.28: Stakeholders feedbacks on further breakdown of the table above specifically for road construction

The data in the table above covers only the Danish national roads for which the Danish Road Directorate is in charge (state roads), i.e. 3790 km roads (including motorways) (DK)

Table II.29: Stakeholders feedbacks on estimation of average transport distances for aggregates and other construction materials (concrete, asphalt, binders, etc.)

All construction material use is reported in our carbon calculator and transport distance is recorded for each tonne delivered. 85% of materials are transported by road. Data as reported by the Highways Agency supply chain via the Agency's carbon footprinting tool (UK)
It is up to the contractor to decide what materials to use (see performance approach for GPP) Many aggregates are locally excavated (sand), but stone aggregate for asphalt is imported from the surrounding countries (NL)
Aggregates: 30km (one way) Lime: 50 km (one way) Asphalt: 40 km (one way) (DK)
For some civil works it is possible to know the distances (around 30 km), but this is not usually done, because each enterprise can chose the supply depending on its own business deals. If considerable, the environmental impacts are evaluated in the E.I.A.. If there is no need of E.I.A., these transportation impacts are not counted (IT, local authority)
For this part, in the IRF GHG Calculator, CHANGER we assess environmental impacts in terms of CO2 emissions produced by fuel consumption. The equation takes into consideration tons of material moved, number of Km, mode of transport chosen (rail, road or inland waterways). For a full description of CHANGER and it's methodology including examples of calculations made on real projects see: "Measuring the carbon footprint of road construction using CHANGER", International Journal of Pavement Engineering, June 2012 available at: http://www.irfnet.org/files-upload/pdf-files/CHANGER_Article_Journal%20Pavement_Engineering_2012.pdf (IND Association)
This will be depending on the distance of the jobsite and primary or processed raw materials.
The average transport of the EU steel industry by-products applied in the road construction cannot be estimated but it should be supported the use of slag in the public construction works, as road/highways, located near-by a steel production plant in order to promote resource efficiency and reducing the impacts on the environment (IND Association)

Table II.30: Stakeholders feedbacks on trend in the choice of pavement type preferred

Albeit with quieter surface.
Asphalt roads have a better LCC, also related to the fact that in the Netherlands porous asphalt due to noise regulation is the standard wearing course for the motorway network
Semi-rigid is very slowly increasing (composite pavement)
kerosene and other oil used in aiport have an effect of solvent for bitumen, so asphalt requires an anti-kerosene treatment. Rigid pavement are slowly becoming more used in the airport field, replacing the need of this treatment.
It depends on the road types (national or provincial level), on the load types (traffic intensity and percentage of bulky traffic) and also on the road elevation.

Table II.31: Stakeholders feedbacks on lengths of roads bought through public procurement in a year

<table>
<tr><th>Procurement volumes</th></tr>
<tr><td>Averaged over the last three years, this is circa 70km of road an additional 190 lane km (gross) (UK)</td></tr>
<tr><td>55 km in 2009, 371 km in 2010 (note new roads, not maintenance, only national freeways under responsability of Rijkswtaerstaat) No data found (yet) for the whole of the Netherlands (NL)</td></tr>
<tr><td>Procurement volumes (km): the following data refer to the annual growth of roads km (both regional and national) for the period 2003 – 2008 (source: ISTAT)
<table>
<tr><td>2003-2004</td><td>2.509</td></tr>
<tr><td>2004-2005</td><td>78</td></tr>
<tr><td>2005-2006</td><td>869</td></tr>
<tr><td>2006-2007</td><td>5.839</td></tr>
<tr><td>2007-2008</td><td>1.567</td></tr>
</table>
For 2012 data refer to highway and other roads of national interest. We know that 1343 km of roads have been bought through Public Procurement and, in particular, 1341 km of road maintenance and 2 km of road construction (Source: ANAS) (IT)
The Autonomous Province of Trento has bought in the last year 9826 m^3 of recycled materials. The Autonomous Province of Trento manages about 2000 km of roads.</td></tr>
<tr><td>~1300 km/year according to the national statistics institute (Turkey)</td></tr>
</table>

Table II.32: Stakeholders feedbacks on experiences in application of GPP criteria

	% projects containing GPP criteria	Respond of the contractor
Own technical standards and specifications acceptance of recycled and reused materials provided performance requirement is achieved (UK)	100 %	Good understanding and a strong desire to align with the overseeing organisations corporate ambitions and standards.
DuboCalc,(Sustainable Building Calculator; a LCA based tool used in the Economic Most advantageous Bit (NL); http://www.youtube.com/watch?v=LJY9QzxlW2w CO2-performanceladder (http://skao.nl/index.php?ID=45), National Criteria for green public procurement http://www.pianoo.nl/sites/default/files/documents/documents/volledigecriteriadocumentwegen.pdf CO2-performanceladder and the national criteria for green public procurement are easy to use, DuboCalc is a recent addition and therefore needs some explanation in the projectteams. We have a national database for environmental data for building products. On an national level there is coordination and cooperation between involved authorities, government, contractors, consultants et cetera See http://duurzaamgww.nl/	100 %	The national criteria were already operational. Many of the issues mentioned were already common practice. Introduction of the CO2 performance ladder after a beginning period was not facing problems. One exeption, for small entrepreneurs it is a little bit more difficult to get to the higher levels. But bigger contractors are not having difficulties. In stead of that they benefit because they know where there is a possibility to reduce emissions, energy and therefore costs. Dubocalc is being accepted and regognised as a good tool for sustainable design of a road.
The Autonomous Province of Trento (IT) determined in 2012 (with Del. G.P. n° 41/2012) the criteria for the Green Public Procurements. The provincial GPP criteria can be easily summarized as follows: for each road public project (considering 3 phases: project, tender, achievement and maintenance) the 30% of the economic value of each entry in the project (e.g. asphalt, gravel or sand) has the legal duty to be a recycled material (with CE mark- e.g. 100 mc of asphalt are needed, the 30% of the economic value of this entry has to be recycled asphalt, this does not mean 30 mc). In this moment only the bitumen is an exception, while all the other entries, which are necessary for the road construction, are included in the GPPs. To use them the provincial price list is continuously updated with the entries of recycled materials		Usually they do not have problems with them, because they can find in the provincial price list the values of the recycled materials, using these prices it is possible to respect the provincial GPP criteria. On one occasion a contractor asked to utilize recycled materials for the road foundation, instead to use quarrying materials and the technical management gave the permission.
Greenroads rating system: https://www.greenroads.org/ INVEST rating system: http://www.vicroads.vic.gov.au/NR/rdonlyres/BE125F3A-4C18-4888-9396-2D84BD9F513D/0/INVESTMar2011VicRoadsV2.pdf		Contractors often find most difficult to fill in the burocratic formalities to obtain certifications rather than complying to the criteria per se. Paper formalities can be highly costly and time-consuming. The experience with sustainability rating systems provides useful guidance: there has to be some flexibility built in the system in order to allow also those who are not yet able to ensure full compliance with all the criteria to catch up later. Eg. In the rating system different levels of certification are provided (Gold, silver, bronze, etc.) This allows the contractors to move forward by stages and actually function as an incentive to do better thus engaging them into the process rather than cutting them off right at the beginning. The experience with the CO2 Ladderhttp://www.skao.nl/index.php?ID=45) in the Netherlands clearly shows the advantage of the "flexibility approach".

Table II.33: Stakeholders feedbacks on environmental benefits have resulted from the use of GPP criteria, main challenges and constraints and recommendations for the development of the revised EU GPP criteria

Environmental benefits
• Significant recycling and reuse. Greatly reduced waste (incl. a major construction scheme with zero waste to landfill) carbon footprinting by all contractors and a drive to enhance WLC. • More sustainable solutions, better use of material, less emissions in a life cycle, less environmental costs. Better cooperation with partners, producers and contractors • Reducing the amount of disposed wastes from C&D activities, preserving the natural resource of primary aggregates, no enlargement or establishment of landfills, reducing transportation impacts (working on site with mobile plants). • Reduced energy/fuel and water consumption through better optimisation of movements and operations on the work site. • Reduction in energy consumption • • Reduction in maintenance and replacement cost.
Main challenges and constraints
• The balance of VfM v WLC in an environment of economic pressure for optimising capital expenditure. • Keep it simple in procurement (these requirements are quite different from criteria that can be used for the products by companies). And use simple, transparent and a limited number of instruments. Try to avoid details on materials that may hinder innovations. • An very important challenge (now still an obstruction) is a EU database with environmental data on materials. • Once you have set in your organization goals and ambitions on the top level, available instruments, the rest is not so difficult • Challenges regarding price and quality • Resistance to change • Very high life-time as compared to many other products • A lot of training events aimed to technicians and to the enterprises; • More technical-legal constraints (at the moment all the materials, except of the bitumen, for road construction have the legal duty to comply with the 30% of GPP in terms of economic value. The bitumen can respect this criterion) • GPP is not just a question of technical issues to be sorted out, it really requires a change in the way people think and operate both in the public and private sector and that takes a bit of time. GPP does not call for additional elements to the public sector workload. Instead it requires that we carry out an existing function with revised goals and a new mindset. • Create manageable and enforceable criteria. • Thus our suggestion to get experience with smaller projects. • The implementation will be extremely complex and subject to confounding unless a consistent approach is taken to allocation methodologies and system boundaries
Recommendations for the development of the revised EU GPP criteria
• The GPP should be more guiding (like the first part of waste water treatment) and less focused on criteria. Possible criteria should not be prescriptive on details (like prescribing recycling) and have a performance orientated approach. Do not prescribe as we found this to be contra productive if you have to transport recyclable materials from one part of the country to the other). We support the use of LCA based instruments (as dubocalc) to challenge the contractor to come forward with the best sustainable solution over the Life cycle of a road. Verification is rather easy once an objective instrument is developed, quality of data secured, ambition also in financial terms set. Some exceptions may be in place, but only in you want this in all projects, such as such as sustainable wood or the processing of asphalt waste.
• For the use phase criteria on leaching are important. A tank leaching test will be published by CEN/TC 351 shortly and can be used for verification purposes. The substances covered by The Water framework Directive should be addressed when developing the leaching criteria as far as relevant. Additives that contain hazardous substances should be avoided. The manufacturers should be asked to provide any information on the active use of hazardous substances in their product (manufacturer's declaration) so that it is possible to choose a product that contains less hazardous additives, if available.
• The environmental impact of the applied building materials in road construction should be assessed on more criteria than currently put forward by TCN 350.

• The experience gained with sustainability rating systems (US & Australia) should be seriously considered and could certainly serve as a solid base for the development of a EU sustainability rating system. The use of trustworthy and already existing tools (eg calculator like IRF CHANGER (www.irfghg.org), ecolabels, EMAS, etc.) should be considered as a valid mean to simplify verification of compliance with criteria. Criteria should be based on LCA and LCC. • In more general terms, there is an urgent need to demonstrate to procurers and stakeholders how public procurement can be designed to trigger green industrial expansion and innovation. • The private sector continues to innovate and expand on green products, services and solutions that can collectively be used by governments to place their economies on a green growth trajectory. • Procurers however, have little information about these goods, services, technologies, and solutions. Procurers also have limited opportunities to interact directly with the private sector to learn about these opportunities. This is partly because procurement laws and procedures are designed to discourage interaction with suppliers in the interests of protecting the public procurement process from the 'capture' of special interests. • As a result, public procurement calls for tenders and technical specifications are usually designed in a manner that does not encourage the innovation or systemic solutions that are necessary for green growth. Technical specifications are usually designed in a prescriptive manner and based on existing and mature technologies and solutions rather than opening opportunities for innovation. • For procurement to trigger innovation, procurers need to move towards designing performance based specifications that specify needs in terms of performance. This provides opportunities for suppliers to developing innovative solutions and form consortiums to deliver integrated services that will bring resource efficiency and cost saving to the procuring entity. On the macro level, when large procurement tenders are so designed, they will trigger green industrial expansion, create green jobs, trigger multiplier green improvements across supply chains and more. • Most importantly, emerging procurement practices such as first commercial procurement, pre commercial procurement and the procurement of innovation offer further opportunities for performance based specifications to be used as triggers for innovation and green growth.
• Criteria based on LCA or LCC. Establish material classes based on these criteria or scientific research

ANNEX III. TECHNICAL AND ENVIRONMENTAL ANALYSIS

III.1 Assessment rules

Table III.1: PCRs for road infrastructure and construction products

Reference	Scheme	Scope
Road infrastructure		
PCR Basic Module, CPC Division 53 "Land transport infrastructure", version 1.0, dated October 2013	The International EPD®system (ENVIRONDEC)	
PRODUCT CATEGORY RULES DATE 2013-11-21 UN CPC 53211 highways (except elevated highways), streets and roads 2013:20 version 1.01	The International EPD®system (ENVIRONDEC)	EPD for UN CPC 53211 Highways (except elevated highways), streets, roads
Construction materials		
BRE Product Category Rules for Type III environmental product declaration for construction products to EN 15804:2012	BRE	EPD for construction products
PRODUCT CATEGORY RULES AND PCR BASIC MODULE CPC Division: Construction Products and CPC Division 54: Construction Services Version 1.0 Dated 2012-01-09	The International EPD®system (ENVIRONDEC)	EPD for all construction products and construction services for building and other construction works
PRODUCT CATEGORY RULES DATE 2013-05-16 UN CPC 3744 cement 2010:09 version 2.0	The International EPD®system (ENVIRONDEC)	EPD for concrete cement or average cement
PRODUCT CATEGORY RULES DATE 2013-02-12 UN CPC 375 concrete 2013:02 version 1.0	The International EPD®system (ENVIRONDEC)	EPD for concrete
PRODUCT-CATEGORY RULES EN 15804 NPCR 020 Issue date: 28.03.2012 Precast Concrete Products	Epd-norge The Norvegian EPD Foundation	EPD for concrete products (paving, building products, infrastructure products)
PRODUCT-CATEGORY RULES (PCR) for preparing an environmental declaration (EPD) for Product Group Asphalt and crushed stone NPCR 18 November 2010	Epd-norge The Norvegian EPD Foundation	EPD for crushed stone and asphalt
North American product category rules (PCR) for ISO 14025 type III environmental product declarations (EPDs) and/or GHG protocol conformant product 'carbon footprint' of concrete adopted November 30, 2012	Carbon leadership forum	EPD for concrete and concrete component (cast in place concrete , precast concrete, mass concrete, concrete masonry units)

Table III.2: Examples of EPDs for road infrastructure and construction products

Product group	Product/Company/Model	Scheme	Observations
Road infrastructure	Acciona, Spain. N-340 road. Reg. no. S-P-00516. On 19.12.2013	The International EPD®system (ENVIRONDEC)	EPD of a Spanish road, N -340 in Sector E -40, Elche (Alicante)
Product group	**Product/Company/Model**	**Scheme**	**Observations**
Ready-mix concrete	Buzzi Unicem SpA	The International EPD®system (ENVIRONDEC)	5 EDPs models (R_{CK} 10-15-20-25-30)
Cement	Buzzi Unicem SpA	The International EPD®system (ENVIRONDEC)	EDPs models for various cement typologies (I 52,5-II ALL 42,5-II BLL 32,5 - IV AP 42,5-I 42,5-IV BP 32,5-IV A 42,5)
Cement	Çimsa Çimento San. Ve Tic. A.Ş. EPD-CIM-2012111-E on 21.03.2012	Institut Bauen und Umwelt (IBU)	1 EDPs model (CEM IV / B(P)32,5R)
Cement	Verein Deutscher Zementwerke e.V. EPD-VDZ-2012111-D on 16.03.2012	Institut Bauen und Umwelt (IBU)	
Steel	Celsa Steel service OY	The International	

reinforcement for concrete		EPD®system (ENVIRONDEC)	
Concrete	Betong Øst NEPD nr: 123N Date: 31.10.2013	Epd-norge. The Norvegian EPD Foundation	Ferdigbetong B25 M60
Asphalt	FAV (Foreningen Asfalt og Veiservice) NEPD nr: 216N	Epd-norge. The Norvegian EPD Foundation	AGB 11 asfalt (bransjegjennomsnitt)

Table III.3: Data on use of resources and additional environmental information to be provided according to the PRC UN CPC 53211 highways (except elevated highways), streets and roads

Environmental performance-related information	
Use of resources	Non-renewable resources: Material resources, in kg Energy resources, in MJ
	Renewable resources: Material resources, in kg Energy resources, in MJ
	Secondary resources: Material resources, in kg Energy resources, in MJ
	Recovered energy flows, in MJ
	Water use (including total amount of water and direct amount of water used by the core process), in L
Waste production	Hazardous waste (as defined by regional directives), in kg Non-hazardous waste, in kg
Additional environmental information	
Impacts on biodiversity	Permeability of transport corridors, safety and mortality, disturbance of surrounding habitats, conservation of habitats, natural flora and fauna, created natural values
Noise and vibrations	Direct impact from infrastructure construction, maintenance and operation as well as from traffic. Impacts on relevant areas such as residential areas, sensitive biotopes or recreational areas. Measurements for improvement of impacts from traffic noise and vibrations.
Management of materials and substances	Chemical products that contain substances meeting the criteria of Substances of Very High Concern (SVHC) in REACH article 57 shall be declared. Articles containing SVHC, appearing on the REACH Candidate List, in a concentration above 0.1 % (w/w) shall be declared.
Water management	Declaration of the environmental impacts on water flows, groundwater levels, and water quality, both temporary under construction and permanent during operation of the infrastructure Description of the measures taken to ensure an acceptable ecological status in water flows, groundwater levels, and water quality. A description how non-harmful groundwater levels could be maintained during operation of the infrastructure.

Table III.4: Screening rules applied for the review of the LCA studies

Item	Cut-off (minimal requirements)	Scoring
Authors		-
Year		
Title		
Reference (journal, pagg…)		-
Type of study (e.g. attributional/consequential LCA according to ISO 14040, PCRs, PAS 2050:2011, PEF)	QUALITY OF SCOPE: ☑ Functional unit properly defined and relevant for this revision ☑ Scope coherent for the goal of the study ☑ Assumptions of the study shall respect ISO 14040 standard	S_{SCOPE} 5 = coherent cradle to grave LCA for road construction 3 = coherent LCA for road construction (e.g. cradle to grave LCA for one or more life cycle phases or one or more layers as sub-base, road base, base course, concrete slab, surface course, etc.) 1 = streamlined LCA for some products of interest products of interest (e.g. construction materials and products)
Scope		
Functional unit		
System boundaries (stages and process cut-off)		
Assumptions (e.g. Allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**		S_{DATA} I) Temporal, geographical and technological representativeness evaluated for each stage: 5 = high quality ▪ data refers to less than 5 years ago ▪ data for specific country of interest and relevant for the EU GPP ▪ data for specific technology/materials of relevance for the EU GPP 3 = average quality ▪ data refers to 5-10 years ▪ average data at continental level and relevant for the EU GPP ▪ data reflecting the average technology/materials used 1 = low quality ▪ data refers to more than 10 years ago ▪ average data at world level ▪ Data related to technologies/materials not often used II) the overall score for data is the average of the points assigned to each single stage
Impact assessment categories/methods	☑ Satisfactory broadness (at least one indicator is of interest respect to the indicators identified in the LCA review)	$S_{IMPACTS}$ 5 = satisfactory broadness (with respect to the impact categories identified in the Preliminary Report Chapter 3 paragraph 3.1.1.2.1) AND all indicators of interest are evaluated as A or B (best in class) according to ILCD 3 = at least one indicator is of interest (with respect to the impact categories identified in the Preliminary Report Chapter 3 paragraph 3.1.1.2.1) AND evaluated as C (average class) according to ILCD 1 = at least one indicator is of interest (with respect to the indicators identified in with respect to the impact categories identified in the Preliminary Report Chapter 3 paragraph 3.1.1.2.1)
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	☑ The outcomes of the study must be relevant and applicable to the revision process	$S_{OUTCOMES}$ 5 = The outcomes of the study are of high relevance for the criteria revision and they can be directly used to address some key-issues 3 = The outcomes are somehow of relevance for the criteria revision and they can be directly used to address some key-issues 1 = The outcomes are somehow of relevance for the criteria revision and they can be partially used to address some key-issues

Strengthens and weakness of the whole study, general comments		$S_{ROBUSTNESS}$ 5 = The overall quality of the study is considered good and sensitivity analysis is performed to analyse and manage most important sources of uncertainty and variability 3 = The overall quality of the study is good (in terms of modelling, assumptions, data gaining, impacts assessment, presentation and discussion of results, findings) 1 = Minimal requirements of quality are satisfied
Subject to independent review?		S_{REVIEW} 5 = independent 3rd-party review (e.g. certification) 3 = independent review (e.g. paper) 1 = no review

The Recommendations of the ILCD Handbook (EC JRC, 2011b) have been consulted in order to evaluate which assessment methods are more appropriate to quantify impacts for each of the environmental categories. Impacts assessment methods are classified from A to E, where A represents the best in class methods. Classification criteria focus on scientific aspects and stakeholder acceptance. The Table III.5 shows the evaluation of different assessment methods (from A to E, referred to overall scientific acceptation) and the default method recommended for each of the impact categories identified before.

Table III.5: Classification of midpoint (M) and endpoint(E) Impact category methods

Category	**default LCIA method according to ILCD**	**Indicator**	**Classification**	**Methods evaluation (Overall evaluation of science based criteria)**				
				A	**B**	**C**	**D**	**E**
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as Global Warming Potential (GWP100)	recommended and satisfactory)	IPCC (All midpoints)	Recipe(E)	EPS200(E) Ecoind99 (E) LIME (E)		
Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone Depletion Potential (ODP)	recommended and satisfactory),	WMO (All midpoints)	Recipe(E) LIME (E)	Ecoind99 (E)	EPS2000 (E)	
Photochemical ozone formation	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe	Tropospheric ozone concentration increase	recommended but in need of some improvements)		Recipe (M) EDIP2003 LLIME (M) CML TRACI (M) EcoSense (E) LIME (E) Recipe (E)			
Acidification	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	recommended but in need of some improvements	Accumulated Exceedance	CML Recipe (M)	Recipe (E) Ecoin99 (E) LIME (E)		Traci (M) EDIP2003 MEEUP LIME (M)
Eutrophication, terrestrial	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	recommended but in need of some improvements)	Accumulated Exceedance(AE)	CML 2002 EDIP2003 EPS2000 Ecoindic 99			
Eutrophication, aquatic	EUTREND model (Struijs et al, 2009b)as implemented in ReCiPe	Fraction of nutrients reaching end compartment (P) or marine end compartment (N)	recommended but in need of some improvements)		EDIP2003aqu LIME (M) ReCiPe (M)t TRACI CML EPS2000 IMPACT 2002+ (E) LIME (E) ReCiPe (E)			

Recommendations on broadness and appropriateness of impact assessment metrics

References for the evaluation of broadness and appropriateness of impact assessment metrics have been defined, for instance, in the Product Environmental Footprint (PEF) Guide (EC JRC, 2012b). The document proposes a set of 14 environmental impact categories to take into account to perform a coherent life cycle assessment of a product. Recommended impact categories and related assessment methods are provided in accordance with ILCD Handbook (EC JRC, 2011b).

EF Impact Category	PEF Impact Assessment Model
1.Climate Change	Bern model - Global Warming Potentials (GWP) over a 100 year time horizon.
2.Ozone Depletion	EDIP model based on the ODPs of the World Meteorological Organization (WMO) over an infinite time horizon.
3.Ecotoxicity for aquatic fresh water	USEtox model
4.Human Toxicity - cancer effects	USEtox model
5.Human Toxicity – non-cancer effects	USEtox model
6.Particulate Matter/Respiratory Inorganics	RiskPoll model
7.Ionising Radiation – human health effects	Human Health effect model
8.Photochemical Ozone Formation	LOTOS-EUROS model
9.Acidification	Acumulated Exceedance model
10.Eutrophication – terrestrial	Acumulated Exceedance model
11.Eutrophication – aquatic	EUTREND mode
12.Resource Depletion – water	Swiss Ecoscarcity model
13.Resource Depletion – mineral, fossil	CML2002 model
14.Land Transformation	Soil Organic Matter (SOM) model

The PEF guide also indicates that, depending on the product system and on the intended application, it is possible to narrow the number of impact categories considered. Such exclusions should be supported for instance by: international consensus processes; previous studies of similar systems; Product Categories Rule from other initiatives/ schemes; normalization of results.

III.2 LCA Literature review

Transport

		Scoring
Authors	Treloar G. J., Love P. E. D. and Crawford R. H	
Year	2004	
Title	Hybrid Life-Cycle Inventory for Road Construction and Use	
Reference	Journal of Construction Engineering and Management © Asce, pp. 43-49	
Type of study	Hybrid LCA involves the integration of more reliable LCA data into the comprehensive input-output model. Environmental loading data for specific processes can be associated with each important node in the upstream supply chain, as derived from the input-output data □Treloar 1997□. Unimportant nodes in the up- stream supply chain can then be left in the model using the input- output data, and case-specific data can be inserted for the most important nodes □Treloar et al. 2000□.	1
Scope	The study assesses the total life cycle energy use of road transport: car and truck, for different types of roads **Continuously reinforced concrete** **Plain concrete** **Full-depth asphalt** **Composite, asphalt, and concrete** **Deep-strength asphalt** **Granular** **Deep-strength asphalt on bounded sub-base** **Asphaltic concrete on bounded sub-base**	
Functional unit	1 m road 1 car 1 truck	
System boundaries	The life-cycle energy attributable to roads—including the share of the vehicles using the road—is depicted in Fig. 1, and comprises • Road construction, use □i.e., vehicles□, maintenance, and re-placement and • Vehicle manufacture, use, maintenance, and replacement	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**		3
Calculation methodology/ programme		
Impact assessment categories/methods	Energy inputs	1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The elements of the life-cycle energy attributable to the road are depicted in Fig. 3. The relative importance of the various elements changed considerably over the 40 year life cycle. In the first year, the life-cycle energy comprised • 64% vehicle manufacture □not amortized annually□, • 21% road construction □for Road Type CRC□, and • 15% vehicle operation. At the end of the simulated 40 year life cycle, the total of 6,571,635 GJ for Road Type CRC comprised • 62% vehicle operation □initially third□, • 28% vehicle manufacture and maintenance □initially first□, and • 10% road construction and maintenance at 4% □initially second□ The road type with the lowest life-cycle energy, not including the life-cycle energy associated with vehicles, was ''granular.'' This road type, however, may not stand up well to marginal in-creases in truck traffic—a major determinant of road maintenance requirements—over time □Porter and Tinni 1993□. Other road types found to have low life-cycle embodied energy may also have differential performance. The road type with the highest life-cycle energy, not including the life-cycle energy associated with vehicles, was ''full-depth asphalt,'' which is apparently quite common in Australia. Further research could identify implementation actions for selecting a road design that has lower life-cycle energy implications, but with equal or greater life-cycle performance in terms of the resistance to marginal increases in truck traffic. A broader hybrid LCA, considering environmental implications other than energy □for example, the	3

	environmental effects of construction waste, may result in the identification of a road design that may also reduce other environmental loadings and impacts. Performance characteristics and features that increase car efficiency and road safety would also need to be considered.	
Strengthens and weakness of the whole study, general comments		3
Subject to independent review?		3
		14

		Scoring
Authors	Chester M.V.	
Year	2008	
Title	Life-cycle Environmental Inventory of Passenger Transportation in the United States	
Reference	Dissertations, Institute of Transportation Studies, University of California, Berkeley http://repositories.cdlib.org/its/ds/UCB-ITS-DS-2008-1	
Type of study	the process model approach that identifies and quantifies resource inputs and environmental outputs at each life-cycle stage based on unit process modeling and mass-balance calculations [Curran 1996, Keoleian 1993], and the Economic Input-Output Analysis-based LCA as a general equilibrium model of the U.S. economy that integrates economic input-output analysis and publicly available environmental databases for inventory analysis of the entire supply chain associated with a product or service [Hendrickson 1998].	1
Scope	The study assesses the total life cycle energy use of fuels, vehicles and infrastructure for several transport modes: Automobiles (Sedan, SUV Pickup), Bus (average bus, peak bus, off peak bus), Rail, and Aircraft	
Functional unit	VMT vehicle mile traveled and PMT passenger mile traveled	
System boundaries	• Roadway construction • Roadway maintenance • Parking construction and maintenance • Roadway lighting • Herbicides • Salting • Repair facilities	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	U.S. Federal Highway Administration and EPA Federal Transit Authority PaLATE: Pavement Life-cycle Assessment Tool for Environmental and Economic Benefits; University of California, Berkeley, Berkeley, CA, 2004 EERE 2002, Deru 2007 IPI 2007, EPA 2005, TRB 1991, Census 2002, MR 2007, Guggemos 2005, PaLATE 2004, EPA 2001	1
Calculation methodology/ programme	PaLATE: PaLATE allows specification of parameters for the design, initial construction, maintenance, and equipment used in roadway construction. Ten roadway types are evaluated for this analysis: interstate, major arterials, minor arterials, collectors, and local roadways in both the urban and rural context. Roadways are designed with two major components, the subbase and wearing layers. The subbase includes soil compaction layers and aggregate bases which serve as the foundation for the wearing layers. The wearing layers are the layers of asphalt laid over the subbase. These layers are what are replaced during roadway resurfacing. Specifications for each roadway type were taken from the American Association of State Highway and Transportation Officials specifications for roadway design [AASHTO 2001].	
Impact assessment categories/methods	Energy inputs, greenhouse gas emissions (carbon dioxide, nitrous oxide, methane) and criteria air pollutant emissions (particulate matter, carbon monoxide, sulfur dioxide, nitrogen oxides, lead, volatile organic compounds) associated with the life cycles of vehicles, infrastructure, and fuels associated with each mode.	3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	No conclusions. It is an inventory	1
Strengthens and weakness of the whole study, general comments		5
Subject to independent review?		1

		12

		Scoring
Authors	Chester M. V. and Horvath A.	
Year	2009	
Title	Environmental assessment of passenger transportation should include infrastructure and supply chains	
Reference		
Type of study		S_{SCOPE} 1
Scope	The study assesses the total life cycle energy use of vehicles, trains and airplanes including not just the tailpipe output, but also the manufacturing and maintenance of the machinery, construction and maintenance of infrastructure and finally the production of fuel.	
Functional unit	Passenger-kilometer-traveled (PKT) on road (automobile and bus), train and by airplane	
System boundaries (stages and process cut-off)	Phases: - Material extraction - Manufacturing and construction - Maintenance and use phase End-of-life phases are not included due to the complexities of evaluating waste management options and material reuse.	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Data on on-road vehicles are gathered from U.S. EPA "Fuel Economy Reporting" (2008), National Highway Traffic Safety Administration 2008 "Vehicle Safety Information" and Ward's Communications 2006 "Ward's Motor Vehicle Facts and Figures Southfield" Emission factors are from U.S. EPA "Mobile 6.2" (2003) and other varieties of sources.	S_{DATA} (3+3+1)/3=2.33
Calculation methodology/ programme	Hybrid life cycle assessment (LCA), a combination of process-based LCA and economic input-output analysis-based LCA (EIO-LCA).	
Impact assessment categories/methods	- Energy consumption - GHG - Criteria air pollutants (NO_X, SO_2, CO)	$S_{IMPACTS}$ 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The impact categories in the study are only given in PKT (passenger-kilometer-traveled) and are not normalized for comparison. The study finds that approx. 70% of the total energy use of a road vehicle is from the active operation phase. The three other large contributors are fuel production, vehicle manufacturing and construction of infrastructure. For the greenhouse gases the GHG emission is approx. 63% higher for the life cycle as compared to vehicle tailpipe operation. The emission of GHG during construction accounts for approx. 10% of the total emission of GHG during the full life cycle. It is concluded that less use of concrete combined with lower energy input and GHG-intensive materials can reduce the emission of GHG significantly. The NO_X emission from automobiles are mainly from active operation and construction of infrastructure, and the total automobile SO_2 emissions 19–26 times larger than operational emissions and are caused by vehicle manufacturing and maintenance, roadway construction and operation (particularly lighting), parking construction, and gasoline production. Finally, the CO emission from automobiles is dominated by the operation phase. Due to the large potential impacts from the use stage it is concluded that the total emissions from the full life cycle is most efficiently reduced by lowering the emissions from operational components.	S_{OUTC} 1
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ 3
Subject to independent review?		S_{REVIEW} 3
		13.33

		Scoring
Authors	Mithraratne N.	
Year	2011	
Title	Lifetime liabilities of land transport using road and rail infrastructure	
Reference	NZ Transport Agency research report 462. 100pp.	
Type of study	The study used the product-based LCA method (ISO14040 2006; ISO14044 2006). However, the results were limited to GHG emissions, cumulative energy demand, and quantity of contaminants delivered to water bodies. Although traffic delays and rolling resistance could	S_{SCOPE} 3

	influence GHG emissions and cumulative energy demand, these were not quantified.	
Scope	The purpose of this research project was to establish the baseline performance of the current road and rail infrastructure used for the transport of passengers and freight in New Zealand in terms of primary energy, GHG emissions, and contaminant delivery to water bodies	
Functional unit	• road infrastructure – a lane-kilometre of a specific type of road (motorway, state highway, urban local road, rural local road, special-purpose road) per annum (lane-km/annum) • rail infrastructure – a kilometre length of single rail track (primary and secondary) per annum (km/annum) • freight transport – a tonne of weight transported over a kilometre distance, using medium/heavy commercial vehicle, light commercial vehicle (LCV), or rail freight wagons (tkm) • passenger transport – a kilometre distance travelled using a specified mode (eg car, van, bus, train, etc) by a passenger (pkm)	
System boundaries (stages and process cut-off)	The system boundary in this study covered the extraction of raw materials through to disposal of waste materials (or recycling), reasoning that all life cycle inputs and outputs were relevant for consideration, regardless of their physical location or the time period considered. ISO14040 recommends that 'resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study'. All unit processes within the system boundary that were likely to make a material contribution to cumulative energy demand, GHG emissions, and quantity of contaminants were included. Road and rail infrastructure systems were limited to carriageway (pavements and bridges) and rail track (track formation, bridges and tunnels), respectively. The following inputs were omitted from the analysis because of a lack of readily accessible data: • earth-moving for pavement and track formation • on-site wastage of construction materials.	
Assumptions (e.g. allocation)	Subgrade is assumed to have a useful life of 100 years. The foundation (base course and sub-base) is expected to last 40 years for unbound granular pavements, and 50 years for structural asphalt pavements. The useful life of the wearing course depends on the type of surfacing and the level of traffic (see table 2.3)	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**		S_{DATA} 1
Calculation methodology/ programme		
Impact assessment categories/methods	• total life cycle energy consumption • life cycle GHG emissions • life cycle stormwater contamination • life cycle costs by including:	$S_{IMPACTS}$ 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	Lifetime energy use from the construction and maintenance of the pavement structures is dwarfed by the energy use for earth-moving, especially in difficult terrains. In easy terrains (flat sections), earthworks contribute 20% and 13% respectively to the lifetime energy use of state highways and motorways, and 19%, 6% and 9% to urban local, rural local and special-purpose roads respectively. Energy use for earth-moving in difficult terrain is twice as much as the lifetime energy use of a motorway. In difficult terrain (hilly sections), earthworks contribute 67%, 53% and 65% to the lifetime energy use of state highways, motorways and urban local roads respectively. For rural local roads and special-purpose roads in hilly conditions, earthworks contribute 33% and 42% respectively. Both state highways and motorways use 4.5m wide lanes (including shoulders), with unbound granular construction and structural asphalt construction, respectively. Lifetime energy use (excluding the earthworks) for structural asphalt construction is 75% higher than that for unbound granular construction. Local urban, local rural and special-purpose roads use 3.5m wide lanes. However, lifetime energy use for a local urban road is only 10% lower than that for a state highway, while local rural and special-purpose roads are 299% and 171%, respectively, higher than the value for a state highway. While maintenance contributes 33% to the lifetime energy use of local urban roads, contributions by maintenance to the total for rural local and special-purpose roads are 86% and 76%, respectively. Local urban, local rural and special-purpose roads have the same lane width. Lifetime energy use is significantly higher for local rural and special-purpose roads because of the higher use of unsealed surfaces with higher maintenance requirements. Lifetime energy use for different road categories is shown in table 5.24. • The choice of construction type significantly alters the energy use and GHG emissions for the pavement constructions that are commonly used in New Zealand. The unbound granular	S_{OUTC} 5

	construction system provides an environmentally friendly pavement solution, provided a sealed wearing course is used. • At the time of this research, a third of the total network length, especially on rural roads, was unsealed. However, the wearing course construction type has a considerable impact on the energy use and GHG emissions for pavements – because of their high maintenance needs, their energy use and emissions over a 40-year period are four times those of pavements with sealed wearing courses. Sealing the unsealed length of the network could therefore significantly reduce the resource use associated with the existing road infrastructure. • The contribution from earthworks to the energy and GHG emissions for pavements is moderate on flat terrain, but significant on hilly terrain In order to reduce the environmental impacts of the transport sector, it is recommended that the NZTA should specify the use of: • sealed wearing course as the standard practice for pavements, to avoid regular maintenance requirements that lead to higher energy use and emissions, in addition to causing traffic delays • more durable construction types with lower maintenance needs when pavements are constructed on hilly terrains, as construction type has moderate impact on the total environmental impact.	
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ 1
Subject to independent review?		S_{REVIEW} 1
		14

		Scoring
Authors	Hill N., Brannigan C., Wynn D., Milnes R., van Essen H., den Boer E., van Grinsven A., Ligthart T.and van Gijlswijk R. (2012).	
Year	2012	
Title	EU Transport GHG: Routes to 2050 II The role of GHG emissions from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions	
Reference	Task 2 paper produced as part of a contract between European Commission Directorate-General Climate Action and AEA Technology plc; at website www.eutransportghg2050.eu.	
Type of study		S_{SCOPE} 3
Scope	The purpose of Task 2 of the project was to develop a better understanding of the role /significance of GHG emissions resulting from infrastructure construction and use, vehicle manufacturing, and end of life vehicles (ELVs). In particular, a key objective was to ascertain if consideration of these aspects might influence the optimal pathway to transport sector GHG reduction by 2050. Transport modes: road, rail, aviation and shiping	
Functional unit	GHG emissions during 40 years of service life of a 13 m wide road in Sweden (adapted from Stripple, 2001).	
System boundaries (stages and process cut-off)	Construction and materials Maintenance For different types of road: asphalt-hot method, asphalt- cold method, concrete Operation (lightning) It also considers: GHG emissions from road surface construction and maintenance for different road surface materials, distinguishing between construction and materials congestion and usage. Congestion includes all construction and maintenance related traffic congestion. Usage includes overlay roughness effects on vehicular travel and fuel consumption during normal traffic flow (after Zhang et al (2008))	
Assumptions (e.g. allocation)	Subgrade is assumed to have a useful life of 100 years. The foundation (base course and sub-base) is expected to last 40 years for unbound granular pavements, and 50 years for structural asphalt pavements. The useful life of the wearing course depends on the type of surfacing and the level of traffic (see table 2.3)	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Road construction and maintenance: ICE Database – available to download: http://www.bath.ac.uk/mech-eng/sert/embodied/ Vehicle life cycle: World Auto Steel (WAS) SimaPro (2007) Emission factors for lubricating oil were taken from the SimaPro Ecoinvent database (2007). The database comprises of approximately 4,000 datasets for products, services and processes often used in LCA studies. AEA/CE (2010) The dataset compiled through work carried out by AEA/CE Delft for DG CLIMA has been used to provide emission factors for Li-ion batteries and NiMH batteries. EAA (2011) Information on GHG intensity of virgin and recycled aluminium has been taken from the Environmental report for the European aluminium industry (EAA, 2011). This data has been generated with the LCA software (GaBi) and reviewed by a renowned independent expert. In its	S_{DATA} 5

	recent report the EAA also cite a study done by RWTH-Aachen University, which concluded that up to 95% of the aluminium contained in end-of-life vehicles can be recovered using state-of-the-art and properly adjusted shredders and non ferrous metal recovery plants13.	
Calculation methodology/ programme	Fuels: SULTAN tool	
Impact assessment categories/methods	GHG emissions	$S_{IMPACTS}$ 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	Road Transport: GHG emissions estimated to be between 10-40% of total depending on a range of factors, e.g. surface type, intensity of use, maintenance, lighting/electricity generation mix, etc: • Impacts greater for cars versus buses, coaches per passenger km; • Maintenance and renewal estimated to be ~20% of initial construction emissions; • Street lighting can be responsible for majority (>95%) of operating emissions for roads with high levels of lighting (e.g. urban roads) depending on the electricity mix; • GHG emissions from maintenance-related congestion and surface roughness estimated to be same order of magnitude as from construction/maintenance;	S_{OUTC} 3
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ 1
Subject to independent review?		S_{REVIEW} 1
		14

Road infrastructure

		Scoring
Authors	Häkkinen T. and Mäkele K.	
Year	1996	
Title	Environmental adaptation of concrete. Environmental impact of concrete and asphalt pavements	
Reference	VTT Research notes 1752, 61 p. + app. 32 p.	
Type of study	According to the Nordic guidelines (Annon, 1995)	S_{SCOPE} = 5
Scope	The study assess the environmental impact of road pavements (cement or asphalt) and is based on the estimation of service life of road pavements and environmental burdens caused by production, use and disposal of road pavements.	
Functional unit	1 km of a motorway pavement (in Tampere, Finland) assuming passage of 20,000 vpd (vehicles per day). The service life is 50 years.	
System boundaries (stages and process cut-off)	Phases : - Raw materials extraction, production of materials (bitumen, cement, aggregates) including transportation - Construction - Use (including daily traffic, without considering differences between heavy and light vehicles) - Maintenance (Concrete pavements: 2-3 grindings during 50 years - Asphalt pavements: Finnish (A) or Swedish (B) practice) Also taken into account is the influence of the pavement on: - Fuel consumption by traffic - Noise - Lighting requirements - Dust formation - Concrete carbonation - Traffic congestion during maintenance The following aspects are not taken into account: - Traffic safety and health impacts - Solubility of pavements materials during use and final disposal - Demolition and final disposal of pavement materials - End-of-life	
Assumptions (e.g. allocation)	Differences in concrete and asphalt pavement are the top layer: 220 mm concrete vs 50 mm SMA (split mastic asphalt) + 70 mm ABK (asphalt concrete). The effect of different surface textures on the fuel consumption is not included. The inherent feedstock energy of bitumen is evaluated.	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	The basic data of material and energy flows of the system were collected from the Finnish companies involved. Basic data for bitumen (1992) and for cement (1995) The pre-combustion values are national averages. Emission into air, except for cement and bitumen, were national averages (Konlöf, 1994) National average data for vehicular emissions	S_{DATA} = (1+5+5)= 3.67
Calculation methodology/ programme	LCA methodological framework recommended by the Nordic guidelines (Annon, 1995)	
Impact assessment categories/methods	Impact assessment method according to Ecoscarcity – CML – EPS system version 2.0 - Energy (fossil fuel, electricity, inherent energy) - CO_2 - SO_2 - NO_X - CO - VOC - Heavy metals - Waste generation - Release of substances into water - Dust - Noise (land use) The impact categories in the study are only given in equivalents and are not normalized for comparison.	$S_{IMPACTS}$ = 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material;	<u>Concrete pavements</u>: environmental impacts significantly depend on the cement content in concrete, consequently on the concrete layer depth. The significance of lighting during 50 years is high. <u>Asphalt pavements</u>: environmental impacts significantly depend on the bitumen content in asphalt. Asphalt manufacturing includes aggregates dying, which accounts for high	S_{OUTC} = 5

improvement options)

environmental impacts. Maintenance impacts are also relevant.
Different impact assessment methods are used in the study. With some there were no significant differences between the two pavements, some valuation methods showed that concrete had higher environmental burdens, while others showed that asphalt had a higher environmental impact.
An example of the environmental burdens caused by concrete and asphalt pavements (materials production, paving, maintenance, lighting, traffic congestion, abrasion and noise effect (land use for noise>55dB) and carbonation) in 50 years is shown below

	Concrete pavement Maintenance A	Asphalt pavement Maintenance A	Asphalt pavement Maintenance B
CO_2, tons/km	940	590	670
SO_2, kg/km	1 700	2 500	2 800
NO_x, kg/km	4 700	3 000	3 600
CO, kg/km	2 000	610	670
VOC tot, kg/km	1 000	1 900	2 100
Dust, tons/km	650	1 200	1 200
Hg, g/km	7.6	0.042	0.064
Non-renewable energy, GJ/km	11 000	21 000 *	25 000 *
Noise (land use), ha/km	70	52	52

* Including inherent energy.

In this example the environmental burdens of concrete pavement are:
- 40-60 % higher for CO_2 and
- 30-60 % higher for NO_X
- roughly 3 times higher for CO
- roughly 100 times higher for Hg

as compared with the burdens of manufacture, maintenance and use of asphalt pavement.

And correspondingly are the environmental burdens of asphalt pavement:
- 40-60 % higher for SO_2 and
- roughly 2 times higher for VOCs
- roughly 3 times higher for dust and
- roughly 100 times higher for nonrenewable energy

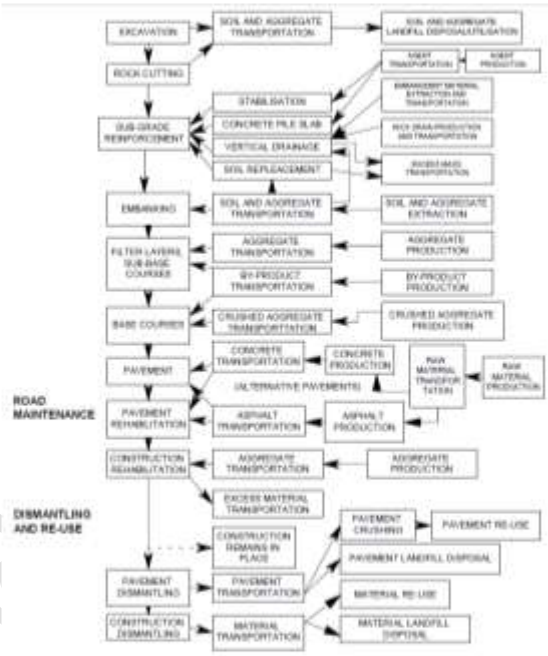
as compared with the burdens of manufacture, maintenance and use of concrete pavement.

Traffic emissions constitute more than 2 orders of magnitude as the emissions during all other phases (including pavement materials, paving, maintenance and lightning).

		Effect of a 0.5% decrease in fuel consumption of traffic	Concrete pavement excluding traffic	Asphalt pavement excluding traffic
Fossil energy	GJ/km	-7,300	7,700	15,000
CO_2	kg/km	- 510,000	940,000	590,000
SO_2	kg/km	- 530	1,700	2,500
NO_X	kg/km	- 11,000	4,700	3,000
CO	kg/km	-2,000	2,000	610

Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 3
Subject to independent review?	Research report of VTT Technical Research Centre of Finland	S_{REVIEW} = 1
		20.67

		Scoring
Authors	Mroueh U-M., Eskola P., Laine-Ylijoki J. and Wellman K.	
Year	2000	
Title	Life cycle assessment of road construction	
Reference (journal, pagg…)	Finnish National Road Administration FINNRA Reports 17/2000 http://alk.tiehallinto.fi/tppt/lca3.pdf	
Type of study	According to ISO 14040-14041, SETAC's 'Code of Practice' (1993), Nordic Guidelines on LCA (Lindfors et al. 1995)	S_{SCOPE} = 5
Scope	To provide a clear and functional procedure for the LCIA of road constructions and for the comparison of alternative structural solutions. Comparison of industrial by-products and conventional materials employed in road construction	
Functional unit	- -1-km-long section of road [width 12 m=2* (3.75 m lane + 2.25 m hard shoulder – depth 5 m - Sub-ground: width 17 m, depth 5 m and length 1 km]. Service life is 50 years. - the quantity of by-product used in the road construction in the landfill disposal alternative Seven different case studies are analysed with different sub-bases:	

	・ Natural aggregate (R1): 250 mm ・ Ash 1 (FA1), 650 mm + 2% cement, and transport distance of 10 km for fly ash and 100 km for cement ・ Fly Ash 2 (FA2), 350 mm + 2% cement, and transport distance of 10 km and 100 km for cement ・ Fly Ash 3 (FA3), 350 mm, and transport distance of 10 km ・ Crushed Concrete 1 (CC1), 150 mm, and transport distance of 10 km ・ Crushed Concrete 1 (CC2), 200 mm, and transport distance of 10 km ・ Blast-furnace slag (BFS), 250 mm, and transport distance of 50 km Regarding the road construction with blast furnace slag, the filter layer also consists of granulated blast-furnace slag whereas the other road constructions include sand in the filter layer of the pavement	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction and materials production (including materials transportation) - Construction phase including earthworks with alternative foundation of the sub-grades (weakly bearing and compressible soft clay extending to a depth of 5 m): 1. <u>Shallow layer of weak soil</u>: a) soil replacement; b)Soil stabilization with cement (100 kg/m^3) 2. <u>Deep layer of weak soil</u>: c) deep stabilization with cement (120 kg/m^3) and stabilised clay capping layer; d) vertical drainage (1 m of drain interval) - Use phase (excluding daily traffic from vehicles using the road) - Maintenance End of life is excluded  Activities/stages excluded from the analysis: - site clearance - functions associated with road use, e.g. road markings, traffic signs and lights - regular or seasonal maintenance, e.g. snow ploughing, road salting and sanding - traffic emissions, because they are only significant if it is possible to determine the effect of using a material or structure on them - Manufacture and transportation of blasting materials and fuels - Manufacture and maintenance of work machines and lorries - Emissions of COD to water bodies and land use	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and**	Database (excel based LCI) developed within the study. Data collected from Finnish studies, primarily. Because of the local effects of road constructions, primarily local or material-specific data have been used. ・ Storing and loading of fly ash Helsinki Energy (Oasmaa 1996) ・ Transport of fly ash and its placement into road constructions Lohja Rudus (Rämö 1997) ・ Landfill disposal of fly ash Helsingin Energia (Oasmaa 1996) Blomster 1989 City of Vantaa (Markkanen 1996) City of Helsinki (Arovaara 1996) ・ Blasting of rock Lemminkäinen (Ruostetoja 1996)	S_{DATA} = (1+5+5) = 3.67

operation phase **6. End of Life phase**	• Excavation of sand and gravel Lohja Rudus (Rasimus 1996) • Crushing of aggregate Lemminkäinen (Ruostetoja 1996) Finnra 1994 Finnra 1995 • Transport of aggregate Lohja Rudus (Rasimus 1998) • Road construction RIL 156 1995 • Blast furnace slag SKJ-Yhtiöt (Mäkikyrö 1998) • Crushed concrete Lohja Rudus (Määttänen 1998) • Cement Häkkinen and Mäkelä 1996 Finncement (Lundström 1998) • Asphalt Häkkinen and Mäkelä 1996 IVL (Stripple 1995) • Concrete Häkkinen and Mäkelä 1996 Lohja Rudus Oy (Kostiainen 1999) Lime Häkkinen and Mäkelä 1996 Lumber Häkkinen et al. 1997 • Reinforcing steel Häkkinen and Mäkelä 1996 • Repaving Finnra (Komulainen 1998) • Remixing Finnira (Eerola 1998) • Design of pavements/ Finnra 1997 Elg-yhtiöt (Elg 1998) JJ-Asfaltti Oy (Karvonen 1998) Valtatie Oy (Mannonen 1998) VTT Chemical Technology (Siltanen 1998) • Tack-coating VTT Building Technology (Apilo 1998) • Deep stabilisation Betoni-Tekra Oy (Pietikäinen 1999) Junttan Oy (Sohlman 1998) • Vertical drainage Kaitos Oy 1998 Geotechnics Holland BV 1998 Containerships 1998 • Leaching of impurities VTT Chem. Technology (Wahlström et al. 1999) VTT (Wahlström & Laine-Ylijoki 1996)	
Calculation methodology/ programme	Assessment method developed in the study	
Impact assessment categories/methods	Impact assessment: EPS method - BUWAL Ecopoint Weighting assessment by two expert groups comparing the environmental loadings of road construction Environmental loadings examined in the life cycle assessment of road construction: - Resource use Use of natural resources Industrial by-products Energy Fuels Land use - Effluents to water bodies (heavy metals and organic compounds)and compounds leaching into the soil (heavy metals and organic compounds) Leaching of metals (e.g. As, Cd, Cr, Cu, Mo, Ni, Se, Pb, Zn) Leaching or migration of organic compounds from material Cl SO_4^{--} - Emission to air: CO_2 – NO_x - SO_2 – VOC - CO - particles - Wastes: inert waste - Other loadings: noise The emissions of heavy metals and organic substances from leaching are addressed by providing the quantity of leaching substances and a qualitative assessment of the resulting impact. Dust emissions are a significant environmental loading factor, but little measurement data are available. Small particulate matter (SPM) can be more significant than the total amount particles but there is lack of data	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	Energy consumption and atmospheric emissions of the construction of alternative pavement structures, also compared to the traffic emissions (7000 vpd – 1000 heavy) over a period of 50 years The LCIA procedure was used to assess six different flexible pavement constructions (difference in layer thickness and in the use of natural aggregates and recycled/secondary materials) and four different construction methods. The results of the assessment of pavement constructions indicate the production and transport of the materials used in road constructions causes the most significant environmental burdens. Production of bitumen and cement are the most energy consuming single parameters of the construction. The fly ash constructions have the highest total energy consumption. The roads with crushed concrete and a thin asphalt pavement have the lowest energy consumption. The difference of approx. 35 % in weighted environmental loadings. The study also found that lengthening the transport distance of materials, from 10 to 50 km can affect the level of individual loadings by as much as 30% and that a large part of the emissions to atmosphere originates from energy production. In an expert assessment used for creating the inventory analysis procedure it was found that the most important loadings are the use of natural materials, energy and fuel consumption, the	S_{OUTC} = 5

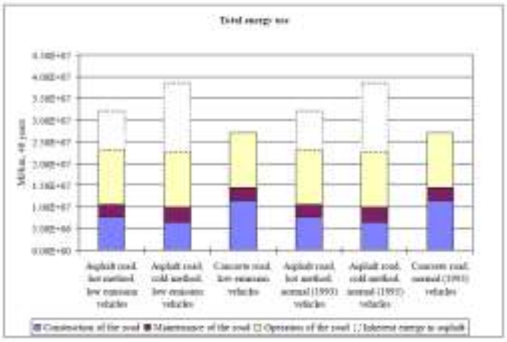
	leaching of heavy metals into the soil, and atmospheric emissions of NO_x and CO_2. <u>Environmental loading earthworks</u>: energy consumption and emissions are high in soil stabilisation and deep stabilisation with cement Energy consumption of these stabilization methods is greater by factors of about 10 and 4, respectively, if compared with the alternative pavement structures.	
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 3
Subject to independent review?	Report of FINNRA Finnish National Road Administration	S_{REVIEW} = 1
		16.67

		Scoring
Authors	Mroueh U-M., Eskola P., Laine-Ylijoki J.	
Year	2001	
Title	Life-cycle impacts of the use of industrial by-products in road and earth construction	
Reference	Waste Management 21, pp. 271-277	
Type of study		S_{SCOPE} = 5
Scope	To evaluate the applicability of the procedure, the use of coal ash, crushed concrete waste and granulated blast-furnace slag in road construction, comparing the use of these secondary products to the use of natural materials in corresponding applications. To create an inventory for comparing the impacts of the most common road construction and foundation methods	
Functional unit	1-km-long section of road [width 12 m=2* (3.75 m lane + 2.25 m hard shoulder. Sub-ground: width 17 m, depth 5 m and length 1 km]. Service life is 50 years Seven different case studies are analysed with different sub-bases: · Natural aggregate: 250 mm and transport distance of 50 km · Fly Ash 1, 650 mm + 2% cement, and transport distance of 10 km for fly ash and 100 km for cement · Fly Ash 2, 350 mm + 2% cement, and transport distance of 10 km and 100 km for cement · Fly Ash 3, 350 mm, and transport distance of 10 km · Crushed Concrete 1, 150 mm, and transport distance of 10 km · Crushed Concrete 1, 200 mm, and transport distance of 10 km · Blast-furnace slag, 250 mm, and transport distance of 50 km Regarding the road construction with blast-furnace slag, the filter layer also consists of granulated blast-furnace slag whereas the other road constructions include sand in the filter layer of the pavement	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction, production and transportation of materials - Construction phase including ground works - Maintenance and operation phase excluding emissions caused by traffic. Only maintenance alternatives are evaluated End-of-life is excluded The following activities are excluded, because of they have no significant impacts when comparing the alternatives: - Site clearance - Functions associated with road use e.g. lane markings, installation of lights, use of lights and traffic signs - Regular and seasonal maintenance - Traffic emissions because they are only significant if it is possible to determine the effect of using a material or structure on them. Though for comparison, traffic emissions were estimated for 7,000 vehicles a day of which 1,000 was heavy duty vehicles	
Assumptions (e.g. allocation)	The production chains of industrial by-products were limited so that the environmental loadings of their production processes were not included	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	LCI of the most common construction materials and unit operations employed in road construction and ground works engineering methods Primarily local or material-specific data were used for the effects of road constructions, together with general Finnish knowledge, which was supplemented by international sources of data where necessary. Average Finnish leaching data was used for industrial by-products. Leaching tests were conducted on natural aggregates and secondary materials during the project. Little measurement data on emission of dust and small particulate matter was found.	S_{DATA} = (1+5+5) = 3.67
Calculation methodology/ programme	An Excel-based life cycle inventory analysis program for road constructions has been developed. No information is available regarding the applied LCA methodology.	
Impact assessment	1. Use of resources:	$S_{IMPACTS}$

categories/methods	- Natural resources - Industrial by-products - Energy and fuel consumption 2. Atmospheric emissions - CO2 - NOx - SO2 - VOC - Particles - CO 3. Leaching into the ground - Heavy metals - Chloride - Sulphate 4. Other loadings - Noise - Dust - Land use Excluded from the inventory: water use, discharges of COD and nitrogen to water, emissions of PAH, heavy metals and methane, ordinary and hazardous waste and accident risks The impact categories in the study are only given in equivalents and are not normalized for comparison.	= 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The study compared six different industrial by-product materials used as sub-base material and compared with the use of natural aggregate material. It is concluded that the production and transport of the materials used in road construction causes the largest potential environmental impacts. In a case study (a fly ash road construction) asphalt accounts for 57% of the energy consumption and the manufacture of cement constitutes 25% of the total energy consumption. The share of transport accounts for 15-30% of the energy consumption. Furthermore, the production of bitumen and cement, crushing of materials and transport of materials are the most energy consuming activities during the life cycle of the road construction. The consumption of natural materials and leaching behavior were also considered to be of great significance. In the investigated case study the blast furnace slag and crushed concrete resulted in reduced potential environmental impacts compared to a reference construction with the use of natural aggregate. This result cannot be generalized to other studies as the transport distances can change the conclusion.	S_{OUTC} = 5
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 3
Subject to independent review?	Peer review paper	S_{REVIEW} = 3
		18.67

(in average 70 Mt/y in Finland)

		Scoring
Authors	Stripple H.	
Year	2001	
Title	Life Cycle Assessment of Road. A Pilot Study for Inventory Analysis	
Reference	ILV Report (2nd Rev.)	
Type of study	According to SETAC, 1992	S_{SCOPE} = 5
Scope	Comparison of the life cycle phases of two asphalt pavements (hot mix and cold mix asphalt) and one concrete pavement	
Functional unit	1 km of a road section with a width of 13 m. Service life is 40 years	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction and materials production (including transportation) - Construction (including also road markings, traffic signs, vegetation etc) - Use (data on daily traffic are also provided for comparison) - Maintenance and operation (including also road markings, traffic signs, vegetation etc) Phases/stages excluded from the analysis: - production and maintenance of vehicles or machines themselves - manufacturing of production plants (refineries, cement or asphalt plants, etc.). Their operation is included - The slow long-term processes such as uptake of CO_2 in concrete (carbonation) and in-air	

	oxidation of bitumen are not included in the calculations.	
Assumptions (e.g. allocation)	The inherent energy use can be treated as a resource use of bitumen	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	The work performed by Stripple via this project has resulted in a computer model (SETAC) Data has been measured from the processes. Swedish data for electricity has been used (primarily hydropower and nuclear power) which gives rise to the conclusions from the study where the energy consumption causes relatively low emissions of CO_2 etc. LCI includes: 1) Electricity production (Production of electrical energy, data from Swedish average electricity); 2) Emissions and energy consumption during transport by truck; 3) Sea freight (shipments); 4) Diesel driven maintenance vehicles; 5) Excavation classes and weight/volume conditions for fill; 6) Wheel loaders; 7) Excavators; 8) Dumper; 9) Road rollers; 10) Asphalt pavers; 11) Production of bitumen; 12) Tack coating using bitumen emulsion; 13) Production of crushed aggregates; 14) Extraction of pit-run gravel and sand; 15) Production of quicklime; 16) Production of cement; 17) Production of cement based road concrete; 18) Production of polyethylene plastic; 19) Sand gritting of road in winter road maintenance; 20) Extraction of salt for winter road maintenance; 21) Salt gritting of road in winter road maintenance; 22) Snow clearance; 23) Mowing of verges; 24) Clearing of verges; 25) Trench digging in maintenance of road; 26) Erection and removal of snow posts; 27) Washing of road signs; 28) Washing of roadside posts; 29) Felling; 30) Synthetic rubber – EPDM; 31) Aluminium; 32) Steel Production; 33) Zinc production; 34) Foundation reinforcement using cement/lime columns; 35) Foundation reinforcement using concrete piles; 36) Wildlife fences; 37) Road markings, signs, lighting, traffic lights and other railings and fences; 38) Production of hot mixed asphalt; 39) Production of cold mixed asphalt; 40) Cement stabilisation of base course in concrete road construction; 41) Laying of concrete wearing course in concrete road construction; 42) Exposure of aggregate on concrete carriageway; 43) Sawing and sealing of joints in concrete road construction; 44) Laying of road markings; 45) Surface milling of concrete and asphalt paving; 46)Operation of the road – complementary activities	S_{DATA} = (1+5+5)= 3.67
Calculation methodology/ programme	The methodology used in this study for LCA has, as far as possible, followed the recommendations from SETAC (Society of Environmental Toxicology and Chemistry).	
Impact assessment categories/methods	- Total energy use - CO_2 - NO_X - SO_2 The impact categories are only given in equivalents and are not normalized for comparison.	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The study compares three different types of road surfaces (asphalt hot and cold methods and concrete) and finds that the concrete surface has the highest impact in all four impact categories. Mainly due to construction and for a smaller part due to maintenance. The total energy consumption in construction, operation and maintenance has been calculated as around 23 TJ for an asphalt surface and 27 TJ for a concrete surface. Energy differences are small between the cold and the hot methods for asphalt. The operation of the road makes up a large part of the total energy consumption. The study also shows that the impact of a road with lights and traffic control are twice as big as the same road without lights and traffic control (electrical energy for road lightning and traffic control is 12 TJ).  *Fig. Total energy consumed for three different road surface materials and two different engine alternatives for a 1 km long road during 40 years of operation.* Finally a rough calculation of the energy consumption for traffic on the section of road during a corresponding 40-year period, shows a total consumption of 229.2 TJ with the assumption of 5000 vpd. 90-95 % of the total energy use comes from traffic, so this is the most important phase of a road. Next after the use phase, the construction phase has the second largest impacts The maintenance causes the third largest potential environmental impacts The operation of road only accounts for minor parts of the total emissions.	S_{OUTC} = 5
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 3
Subject to independent review?	Research report carried out by ILV in collaboration with the National Road Administration Second Rev. Ed.. IVL	S_{REVIEW} = 3

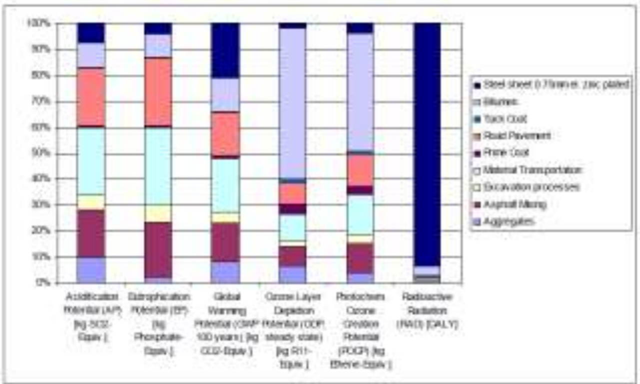
		20.67

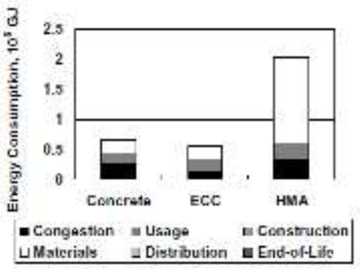
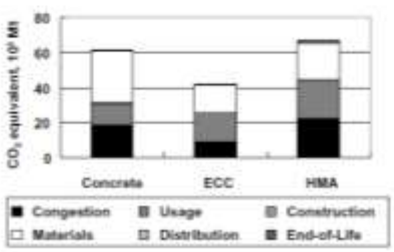
		Scoring
Authors	Chappal M., Bilal J.	
Year	2003	
Title	The environmental road of the future. Life cycle analysis. Energy consumption and greenhouse gas emissions.	
Reference	Colas report	
Type of study		S_{SCOPE} = 3
Scope	Contribution of 20 different road pavement techniques on energy use and GHG emission	
Functional unit	Unit of material (manufactured and placed). Life time is 30 years	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction and materials production (including transportation of raw materials to the mixing plant: refinery 300 km; quarry 75 km; cement works 150 km; steelwork 500 km and transportation of construction products from the mining plant: 20 km) - Construction - Use (different traffic classes describing the number of light and heavy duty vehicles per day) - Maintenance 20 different road construction techniques have been considered, as 1) asphalt concrete, bitumen-bound gravel, high modulus asphalt concrete; 2) warm asphalt mixes, bitumen emulsion mixes, grave-emulsion; 3) cement-bound gravel, gravel and special road binder mix (80 % of clinker replaced with crushed slag), active joint; 4) concrete cement free slab or continuously reinforced pavements; 5) treated soil; 6) in-situ hot recycling or in-situ cold recycling with bitumen emulsion; 7) hot recycled asphalt mixes	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**		S_{DATA} = 1
Calculation methodology/ programme		
Impact assessment categories/methods	- Energy consumption - GHG	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	<u>Manufacture and placement</u> - Concrete cement: energy consumption about 700-1,100 MJ/t – GHG 140-200 kg/t - Hot or warm mixes: energy consumption about 500 and 700 MJ/t - – GHG 30-60 kg/t - Cold mixes: Energy consumption about 300-400 MJ/t – GHG 10-20 kg/t - In situ treated soils (cold) as dug" gravel, active joint, etc.: energy consumption in average 150 MJ/t <u>Pavement structure</u> - Concrete cement: energy consumption about 800-1200 MJ/m^2 – GHG 100-160 kg/ m^2 - Hot mixes and composite pavements: energy consumption 550-850 MJ/m^2 - – GHG 65-90 kg/ m^2 - Emulsion cold mixes and composite pavements with special hydraulic binders or active joints: energy consumption about 450-700 MJ/m^2 – GHG 40-45 kg/ m^2 <u>Use</u> - traffic consumes 10-345 times more energy and 10-400 times more GHG emissions than road construction and maintenance, depending on light or heavy traffic	S_{OUTC} = 3
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$
Subject to independent review?	Industrial report.	S_{REVIEW} = 1
		9

		Scoring
Authors	Hoang, T., Jullien, A. and Ventura, A.	
Year	2005	

Title	A global methodology for sustainable road. Application to the environmental assessment of French highway	
Reference	10DBMC Int. Conference of Building Materials and Components, Lyon, 17–20 April, 2005	
Type of study	ISO 14040-43 (1997-2000)	S_{SCOPE} =3
Scope	Assessment of the life cycle of two different highway sections in France, one with asphalt concrete (AC) and the other with reinforced concrete (CRC). Life time is 30 years	
Functional unit	1 km of highway designed for heavy traffic (750 heavy vehicles/day/lane)	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction and materials production, including transportation - Construction - Maintenance: <u>after 16 years</u>, the upper Continuous Reinforced Concrete (CRC) layer is covered by a surface dressing and by a 2.5 cm Super Thin Asphalt Concrete (STAC); <u>after 30 years</u> the wearing course is reinforced by a 6.5 cm Thick Layer Asphalt Concrete (TLAC) and 2.5 cm STAC	
Assumptions (e.g. allocation)	Materials feedstock energy is not taken into consideration	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	LCI on natural aggregates, recycled steel, clay, limestone, concrete, cement, bitumen, iron, crude oil Crude oil transport (Eurobitume, 1999) Transportation distances (Michelin, 2004) Airborne emissions (EMEP/CORINAIR, 2001)	S_{DATA} = (1+3+3)/3= 2.33
Calculation methodology/ programme	A fully modular tool Elementary Road Modulus (ERM) for the inventory of input/output flows has been developed	
Impact assessment categories/methods	- Energy use - CO_2 - SO_2 - NO_x	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	Energy consumption is above 250 GJ in the construction phase. Maintenance represents 8% and 21% at years 16 and 30 respectively. Environmental impacts of materials transport and equipment is small during the construction phase (around 8% for energy consumption and 4% of the CO_2 emissions), due to the major contributions of sub-systems as cement works (38% of energy consumption, 62% of CO_2 emissions, 61% of SO_2 emissions) and steel production (34% of energy consumption, 30% of CO2 emissions, 29% of SO_2 emissions, 80% of NOx emissions). Transport contribution becomes important during maintenance (about 40% of energy consumption, 48% of CO2 emissions, 79% of SO_2 emissions and of NOx emissions) because of the increasing quantity of crude oil transported by ships for long distances. SO_2 emissions are the most concerned, because ships engines require industrial fuel with high sulphur content.	S_{OUTC} = 3
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?	Proceedings paper	S_{REVIEW} = 1
		11.33

		Scoring
Authors	SUSCON. National Technical University of Athens	
Year	2006	
Title	Life Cycle Assessment of Road Pavement.	
Reference	SUSCON LIFE05	
Type of study	ISO 14040	S_{SCOPE} = 3
Scope	To analyse the environmental impacts of a road	
Functional unit	1 km of a typical urban (C) road (in Cyprus) two 3.5m wide lanes and two 2.5m wide shoulders. Life time is 50 years	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction, materials production (including transportation) - Construction (including site clearance and groundworks) - Maintenance - EoL Use phase is excluded Additional sub-phases in road construction and maintenance consider various road equipment such safety barriers, road markings, traffic signs	

Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	LCI	S_{DATA} = 1
Calculation methodology/ programme	Gabi	
Impact assessment categories/methods	CML (2001) - Abiotic Depletion (ADP) - Acidification Potential (AP) (classification B) - Eutrophication Potential (EP) (classification B) - Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) - Global Warming Potential (GWP 100 years) (classification A) - Human Toxicity Potential (HTP inf.) - Marine Aquatic Ecotoxicity Pot. (MAETP inf.) - Ozone Layer Depletion Potential (ODP, steady state) - Photochem. Ozone Creation Potential (POCP) (classification B) - Radioactive Radiation (RAD) - Terrestric Ecotoxicity Potential (TETP inf.) Normalization factors and evaluation factors according to CML2001 Environmental Score = Characterized Value x Normalization factor x Weighting factor	$S_{IMPACTS}$ = 5
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The environmental impacts of the road life cycle are equally distributed among the construction (51% to the total environmental score) and maintenance (49%). In the construction phase environmental impacts are affected by the material production and transportation processes. Bitumen, asphalt and steel production have large impact during construction. Fuel consumption during the transportation, excavation and pavement processes also contributes to the total impact during construction.  *Fig. Contribution of each construction material/product to the total environmental impact of the construction phase* During the maintenance phase, the wearing course is replaced every 8,5 years. The environmental impact of asphalt is mostly affected by bitumen production and the asphalt mixing process. Bitumen is the largest contributor to the ODP and POCP. GWP contributes by 52%, POC by 24%, EP by 16%, AP by 7%, ODP by 1%, RAD by 0% to the total environmental impact of the road. Energy consumption during the material production processes and diesel consumption during transportation cause large amounts of air emissions contributing to the GWP. The environmental impact of the transportation is attributed to diesel consumption. The large amount aggregates and asphalt transferred during the construction phase is the main reason of fuel consumption during transportation.	S_{OUTC} = 5
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?	Draft report	S_{REVIEW} = 1
		16

		Scoring
Authors	Zhang H., Keoleian G.A. and Lepech M.D.	
Year	2008	
Title	An integrated life cycle assessment and life cycle analysis model for pavement overlay systems	
Reference	Life-Cycle Civil Engineering, pp. 907-912	
Type of study		S_{SCOPE} = 5
Scope	To evaluate the sustainability of rigid pavement overlay designs by means of an integrated LCA and LCCA	
Functional unit	10 km long freeway sections in 2 directions [2*(3.6 m of lanes, 1.2 m of inside shoulder, 2.7 m of outside shoulder)]. Life time is 40 years. 70,000 vehicles with 8% heavy duty trucks. Baseline scenario with annual traffic growth equal to 0% 3 overlay systems are analysed: - an unbounded concrete (concrete) system: thickness 175 mm – design life time 20 years – maintenance: major events at year 11 and year 31 - a hot mix asphalt (HMA) system thickness 190 mm – design life time 20 years – maintenance: major events at year 8 and 28 and minor maintenance events in year 6, 12, 26, and 32 - an alternative engineered cementitious composite (ECC) system (high performance fiber-reinforced cementitious composite HPFRCC): thickness 100 mm – design life time 40 years	
System boundaries (stages and process cut-off)	Phases: - Material production (including transportation) - Construction - Use (overlay usage) - Maintenance and construction- related traffic congestion (user costs: user delay costs, vehicle operating costs and risk of traffic accidents) - End of life management	
Assumptions (e.g. allocation)	Inherent energy of bitumen has been taken into account	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	LCI	S_{DATA} = (3+3+3)= 3
Calculation methodology/ programme	LCA model linked to four external models: (1) a material environmental impact model (SimaPro 7.0) (2) a vehicle emissions model, MOBILE 6.2 (US EPA, 2002), and four localized MOBILE 6.2 data inputs for the winter and summer seasons (SEMCOG 2006) (3) a construction equipment model, NONROAD (US EPA, 2005) (4) and a traffic flow model (KTC 2002) The framework of the LCCA model was first developed by Kendall et al (2006)	
Impact assessment categories/methods	- GHGs - Energy consumption	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The primary energy consumptions for 10 km of the concrete, ECC and HMA overlays are 6.8×10^5 GJ, 5.8×10^5 GJ and 2.1×10^6 GJ, respectively. It is dominated by material production energy, traffic congestion related energy, and roughness related energy. Without considering surface roughness effects, the life cycle energy consumptions of three overlay systems decreases by 23%, 36%, and 14%,respectively. The large amount of primary energy consumption for HMA is the feedstock energy. Carbon embodied in the material is fixed and does not generate CO_2 unless it is burned. Therefore, the GHG emissions of the HMA overlay system is not significantly higher than the other two systems Compared to concrete and HMA, ECC reduces the total life cycle energy by 15% and 72%, GHG emissions by 32% and 37%, and costs by 40% and 58%, over 40 year life cycle  	S_{OUTC} = 5

	The resulting LLCA models enables decision makers to evaluate pavement infrastructure projects from a more holistic, long term perspective while providing criteria for more sustainable infrastructure material selection: - Despite higher initial construction costs, the lower maintenance frequency results in an accumulated agency cost savings for ECC compared to concrete and HMA overlay systems. - User costs account for more than 80% of total life cycle costs in each overlay system. - Since a high traffic volume freeway is considered, congestion-related user time delays are significant. Thus, user costs overwhelmingly dominate total life cycle costs. Minimizing the interruption of traffic flow during construction and maintenance activities over the total life cycle of an overlay is important for highway designers	
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?	Peer review	S_{REVIEW} = 3
		18

		Scoring
Authors	Huang Y., Bird R. and Bell M.	
Year	2009	
Title	A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation.	
Reference	Transportation Research Part D 14, pp.197–204	
Type of study	ISO 14040	S_{SCOPE} = 5
Scope	Development of a model for pavement construction and maintenance, detailing methodology and data sources and application to a case study (an asphalt pavement rehabilitation project in the UK). This case study investigated what effect the speed of delivery of the roadwork had on the traffic and consequently on the fuel consumption and emissions	
Functional unit	- 2.6 km dual carriageway [2*(3.5 m/lane)] of a rehabilitated section of the A30. The northbound traffic was 12,410 vpd and the southbound 14,083 vpd Pavement construction included 200 mm high density macadam (HDM) base and 60 mm dense bitumen macadam (DBM) binder course, with 40/50 mm hot rolled asphalt (HRA) forming the surface layer	
System boundaries (stages and process cut-off)	Phases: - Material production (including transportation) - Construction and construction- related traffic congestion - Use (overlay usage) - Maintenance and maintenance- related traffic congestion - End of life management	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Primary data from UK plants and contractors and from LCA studies reviewed (Huang, 2007). Data on energy consumption from sources as the US Department of Energy, National Crushed Stone Association and the Canadian National Research Council (Zapata and Gambatese, 2005) Data on production of electric power using the industry average of 15 European countries (EURPROG, 1998) Data on production of diesel from the IVL's Report (Stripple, 2005) Data on energy production (electric power, natural gas, petroleum oil) (National Atmospheric Emissions Inventory (2005 report, BUWAL250) Emission limits from EMEP/CORINAIR Emission Inventory Guidebook. Alternative emission limits on diesel engines (European Automobile Manufacturers Association, 2007 and United Nations Economic Commissions for Europe (1999). Emissions from heavy-duty trucks (TRL, 2000)	S_{DATA} = (3+3+3) /3= 3
Calculation methodology/ programme	The model is applied to an asphalt pavement rehabilitation project in the UK, and the micro-simulation program VISSIM is used to model the traffic flow in normal time and during the roadwork, based on the knowledge of traffic data and road configuration. EnvPro (Environmental Program), developed by PTV AG and Newcastle University Transport operations Research Group (TORG), is used to estimate the pollutants from the traffic using the simulation results of VISSIM (PTV and Transport Operations Research Group, 2004). EnvPro calculates the difference in fuel consumption and emissions by comparing two inventories	
Impact assessment categories/methods	EC-JRC (Pennington et al., 2004) and methods recommended by UK Building Research Establishment (BRE) and ISO14047 (Howard et al., 1999; BSI,2003) Impact categories: - CO - NOx - CO2 - HC	$S_{IMPACTS}$ = 1

- PM
- FC (fuel consumption)

Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)

S_{OUTC} = 3

Process		CO (g)	NO_x (g)	HC (g)	CO_2 (g)	PM (g)	Energy (J)
Production	Aggregates	72.2E+03	159E+03	22.8E+03	21.3E+06	133E+03	9.22E+03
	Bitumen	41.8E+03	625E+03	388E+03	83.2E+06	65.4E+03	3.20E+04
	Emulsion	28.4	202	152	0.1E+06	82.2	71.7
	Asphalt	77.4E+03	268E+03	68.3E+03	152E+06	52.5E+03	6.93E+04
Transport	Aggregates	53.1E+03	433E+03	7.2	20.1E+06	1.8	5.40E+03
	Bitumen	6.8E+03	16.1E+03	2.1E+03	3.2E+06	89.8	1.06E+03
	Emulsion	1.1E+03	2.6E+03	328	0.5E+06	14.3	170
	Asphalt	6.7E+03	15.8E+03	2.0E+03	3.1E+06	88.6	1.04E+03
Placement	Tack coat	1.4E+03	2.7E+03	0.12	0.27E+06	77.2	90.8
	Paving	1.5E+03	3.0E+03	0.16	0.34E+06	92.8	137
	Rolling	1.1E+03	2.2E+03	0.10	0.22E+06	63.1	74.0
Total		263E+03	1530E+03	482E+03	284E+06	132E+03	119E+03*

* Density of the fuel is assumed to be 1.0E+03 l/tonne.

Fig 1. Energy use and emissions from stoke-on-trent rehabilitation project

Reducing the duration of the roadwork by 3 days in this project saved fuel use and emissions by the traffic. Savings of CO and PM due to the speedy delivery of the roadwork are comparable to those born by the roadwork itself. The speed of construction does not have significant effect on the HC, CO2, NOx or energy consumption. NOx, CO2 and energy figures between roadwork and traffic per year are comparable; while the difference in CO and PM is of 3 orders of magnitude.

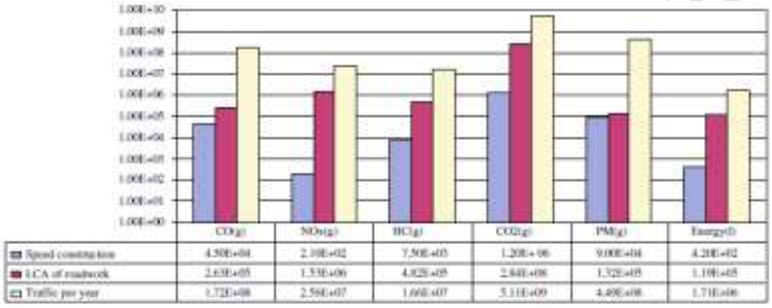


Fig 2. Comparison of fuel use and emissions by traffic, roadwork and speed construction

The speed of delivery of the roadwork will have an effect on the fuel used, and emissions by, any delayed traffic. The additional fuel consumption and emissions by the traffic during the roadwork are significant and this indicates that traffic management at road maintenance projects should be included in the life cycle assessment analysis of such work.

The model gives highway authorities an objective methodology for quantifying the environmental impacts of road maintenance works, including effective traffic management (lane closure, traffic diversion) and phasing of the roadwork into off-peak hours (night shifts).

Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?	Peer review	S_{REVIEW} = 3
		16

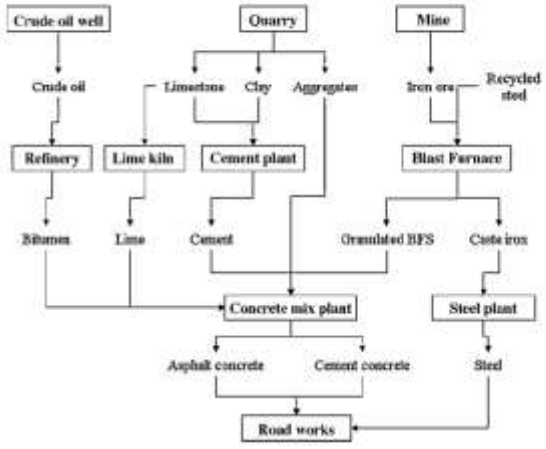
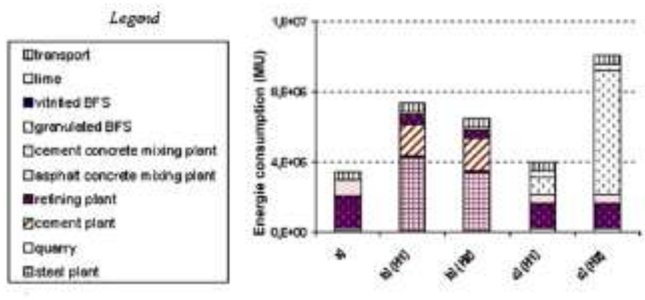
		Scoring
Authors	Santero N.J. and Horvath A.Z.	
Year	2009	
Title	Global warming potential of pavements	
Reference	Environ Res Letts; 4:034011	
Type of study		S_{SCOPE} = 5
Scope	Expanding the current view of the LCA of road pavements by including eight different components: materials extraction and production, transportation, onsite equipment, traffic delay, carbonation, lighting, albedo, and rolling resistance	
Functional unit	1 lane-km with a standard lane width of 3.6 m. Life time is 50 years	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction and material production, - Construction - Use - Maintenance - End of life Each phase is comprised of various components, each of which represents a unique interaction between pavements and the environment. These components are as follows: 1) materials extraction and production, including offsite equipment 2) transportation	

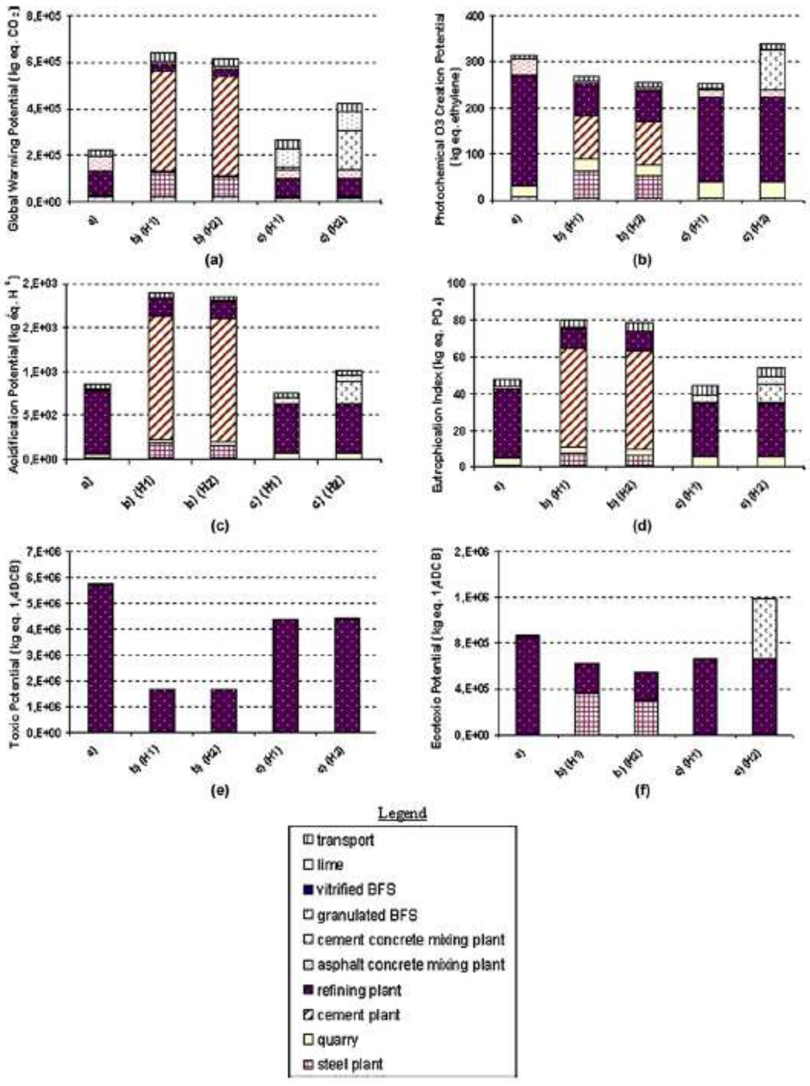
	3) onsite equipment (i.e. pavers, dozers, and millers) 4) traffic delay; 5) concrete carbonation; 6) roadway lighting that varies based on the reflective properties of the surface material 7) albedo 8) rolling resistance	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	**Additional info**	S_{DATA} = 3
Calculation methodology/ programme		
Impact assessment categories/methods	- Global Warming Potential (GWP) (IPCC 2007) (classification A) Similar analyses using other metrics may produce significantly different results. For instance, although onsite equipment is shown to have low GWP ceiling relative to the other life-cycle components, its human health impacts will be much larger due to high exposure to CO, PM and other local pollutants	$S_{IMPACTS}$ = 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	A large range of impacts are possible for the components of the pavement life cycle. The GWP ranges from negligibly small to 60 000 Mg of CO_2e per lane-kilometer over 50 years. Components, such as onsite equipment and carbonation, appear to be relatively small contributors to the overall impact, while others, such as rolling resistance, can have a dominating impact under certain circumstances. Material types and volumes, traffic levels, maintenance schedules, and other project-specific information are critical to understanding which components of the life cycle are the most important from a GWP perspective. The impact of an individual component varies based on its contextual details, such as pavement location, structure, and traffic levels. Rolling resistance (associated with pavement structure and roughness) has the highest-impact potential. The interdependency between many of the components means that, for example, optimizing fuel consumption by maintaining smooth pavements throughout the life cycle may increase the frequency of maintenance activities over the life cycle. This would increase the impact from materials, transportation, onsite equipment, and traffic delay components. Because the environmental gains from reduced fuel consumption are potentially large, the aggregated marginal impact from the other components may be small in comparison. One of the most influential variables is the traffic level that the pavement supports. Whereas rolling resistance and traffic delay are potentially high GWP components for high-traffic pavements, their impact is significantly diminished for low traffic pavements where materials, transportation, and radiative forcing have at least a comparable impact to that of rolling resistance for the low-traffic scenario. The decrease in impact for rolling resistance would be even more pronounced if a very low- traffic road was considered.	S_{OUTC} = 5
Strengthens and weakness of the whole study, general comments	Sensitivity analysis for comparison the GWP impact ranges for components of the pavement life cycle and GWP ranges for low and high-traffic pavements	$S_{ROBUSTN}$ = 5
Subject to independent review?	Peer review	S_{REVIEW} = 3
		23

		Scoring
Authors	ECRPD	
Year	2010	
Title	Energy conservation in road pavement design, maintenance and utilisation	
Reference	Intelligent Energy Europe, Feb 2010, www.roadtechnology.se/ecrpd.eu	
Type of study		S_{SCOPE} = 5
Scope		
Functional unit	1 km of motorway, (traffic 20,500 vpd, 41% heavy), of dual carriageway (traffic 18,500 vpd (30% heavy)), of wide single carriageway (traffic 15,500 vpd, 25% heavy) and of single carriageway (traffic 7,500 vpd, 12% heavy)	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction - Construction of the pavement (asphalt laying and rolling, hot method, in road base, binder	

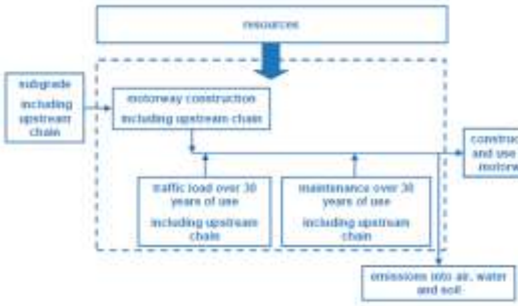
	course and surface course. Application of adhesion layer (tack coat)) - Maintenance of the pavement Scenario A: hot method of recycling in asphalt plant (milling of asphalt surface, asphalt laying and rolling (hot method, surface course), adhesion layer (tack coat) application between asphalt layers) Scenario B: remix in maintenance, hot method in situ, surface course Exclusion from the study: - land preparation and foundation construction (groundworks) - use phase due to daily traffic - end-of-life	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Production data on fuels and energy (Bousted) Production data on raw materials (Gemis database) Transportation data (Emission Inventory Guidebook) Data on road construction and maintenance (TRL and materials suppliers)	S_{DATA} = (3+5+5)/3=4.33
Calculation methodology/ programme	JOULESAVE software to be used at the initial design stage (routes selection) JOULESAVE2 software evaluates the energy required by road construction and maintenance and the energy used by vehicles in the use phase, taking into account road deterioration and rolling resistance	
Impact assessment categories/methods	Energy consumption	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	<u>Construction phase</u>: production of asphalt mixtures and their application consumes approximately 9385- 9986 GJ/km for motorways, 9375-9980 GJ/km for dual carriageway, 3166-3357 GJ/km for wide single carriageway and 3133–3343 GJ/km for single carriageway. The most energy intensive process is the production of asphalt mixtures, which consumes about 92% of energy. Transport of materials and mixtures consumes about 5.7-6.3 % of energy and processes of pavement laying consumes 1.0-1.8 % of energy. <u>Maintenance of asphalt surface (scenario A)</u> consumes approximately 2096-2223 GJ/km for motorways, 1978-2142 GJ/km for dual carriageway, 873-927 GJ/km for wide single carriageway and 898-955 GJ/km for single carriageway. It accounts for 91% of the production process of new mixture, 5.5 % to transport materials and asphalt mixtures and 4 % for the operations. <u>Maintenance of asphalt surface (scenario B)</u> energy savings of 27-29% can be achieved in the case of motorways, 28-33 % for dual carriageway, 27-29 % for wide single carriageway and 31-33 % for single carriageway in comparison to the energy consumption in scenario A. It accounts for 68-71% of the production process of new mixture, 3 % to transport materials and asphalt mixtures and 25-28 % for the remixing and other operations.	S_{OUTC}= 3
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?	Report of a EU FP7 research project	S_{REVIEW} = 1
		15.33

		Scoring
Authors	Sayagh S., Ventura A., Hoanga T., Franc D. & Jullien A.	
Year	2010	
Title	Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures	
Reference	Resources, Conservation and Recycling, 54 (2010) 348–358	
Type of study		S_{SCOPE} = 3
Scope	To investigate the problems involved when performing an environmental assessment of various pavements structures	
Functional unit	1 km of road (lane width is set at 3.5m). Service life is 30-years. a. flexible bituminous pavement: gravel stabilised with bitumen (GB/GB maintenance at years 9-17-25-30 with asphalt (AC)) b. rigid reinforced concrete (RC) pavement (RC/ CC maintenance at years 8-12-15-25with sheet asphalt (AC) at year 30 with cement concrete (CC)) c. semi-rigid gravel-slag (GS) mixture pavement (SS maintenance at years 8-16-24-30 with sand-slag mixture)	

System boundaries	 **Fig. 1.** Diagram of the environmental system.	
Assumptions (e.g. allocation)	Two assumptions regarding allocation procedures of steel plant contribution were estimated for the alternatives cement and BFS pavement, one where BFS is considered as waste from steel production and one where it is considered as a by-product.	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	LCI data sources For cement production data aggregated from various cement manufacturing plants in UK (Lafarge, 2005). Environmental data for bitumen production stem from (Blomberg et al., 1999), steel production from (IISI, 2002), and lime production and cement concrete mixing plant from (Stripple, 2001). For steel plants (IISI, 2002) electricity production has actually been included. As for BFS conditioning processes, only one reference was found (Vares and Häkkinen, 1998). In other cases, local LCI data have been introduced; this would be the case for aggregate production in which a typical pavement production process had been incorporated (Martaud et al., 2007). Such is also the case for asphalt mix plants (Monéron et al., 2006)	S_{DATA} = (3+3+3)/3=3
Calculation methodology/ programme	tool developed by LCPC called ERM (elementary road modulus), which applies the life cycle assessment methodology to road structures: materials (extraction, production, transport, properties), construction techniques (structure, consumption and discharges associated with machines), and maintenance policy.	
Impact assessment categories/methods	- Energy consumption (EE), converted in MJ. - Mass of consumed resources and materials. - Global warming potential (GWP) from (IPCC, 2007). - Acidification potential (AP) from (Goedkoop, 1996). - Photochemical ozone creation potential (POCP) from (Goedkoop, 1996). - Eutrophication index (EI) from (Goedkoop, 1996). - Toxic and ecotoxic potentials (TP and EP) from (Huijbregts et al., 2000).	$S_{IMPACTS}$ = 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The energy use was lowest for asphalt pavement, where bitumen refining and asphalt concrete mixing are the main contributors. For reinforced concrete the steel and cement plant were the main contributors to energy use and in the case with BFS it was the bitumen refining and steel production. The different allocation procedures just had a minor effect on the energy use for concrete pavement. For BFS it had a substantial effect where the 'by-product'- allocation resulted in an energy use more than twice as high compared with the 'waste'-allocation. Refining, cement and steel plants constitute its main contributing processes.  *c. Energy consumption*	S_{OUTC}= 3

	 Fig. 5. Environmental indicators for each studied case (1 km, 30 years, 1 lane). Two distinct mass ratios (0% and 20%) of steel production have been assigned to BFS and tested on indicators results as hypotheses H1 and H2, respectively. Classical indicators have been calculated using a simplified model to allocate output flows into several impact categories. Results show that the structure using BFS contributes to saving binder extracted from natural resources, yet also consumes a larger mass of natural aggregates. All indicators except for toxicity were found to be very sensitive to the choice of H1 or H2 hypotheses	
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 5
Subject to independent review?		S_{REVIEW} = 3
		20

		Scoring
Authors	Milachowski C., Stengel T. and Gehlen C.	
Year	2011	
Title	Life cycle assessment for road construction and use	
Reference	EAPA on-line publication: http://www.eupave.eu/documents/technical-information/inventory-of-documents/inventory-of-documents/eupave_life_cycle_assessment.pdf	
Type of study	LCA according to ISO 14040	S_{SCOPE} = 5
Scope	To quantify the environmental impact of motorways by means of a comparative LCA of motorways with a pavement structure of asphalt and concrete	
Functional unit	1 km long section of a two-lane (on each carriageway) motorway section with a pavement thickness of 85 cm (in Germany). Traffic volume: 52,000 vpd (42,000 cars and 10,000 heavy goods vehiches). Life time is 30 years	
System boundaries (stages and process cut-	Phases: - Construction (including upstream chain)	

off)	- Use phase including maintenance (including upstream chain) (30 year) <u>Construction phase</u>: 1) *Concrete pavements*: constructions with an exposed aggregate concrete surface layer and with surface texture produced by brushing (artificial lawn). Pavements with a noise-reducing porous asphalt top course and mastic asphalt were included in the study. The concrete motorway consists of a frost blanket followed by a hydraulically bound base course, a geotextile interlayer and a concrete surface layer. In the present case, the concrete layer comprises two separate layers in which the surface course is either textured (tc) or is an exposed aggregate concrete 2) *Asphalt pavement*: comprising surface, binder and base course layers supported by a frost blanket. The actual structure depends on the type of surface layer. In the case of porous asphalt (pa), a seal is included. Raw materials transport distance was set to 50 km and, based on field experience. The mixing plant distance to the construction site was set as 20 km.  Exclusion from the study: - a verge of 1.5 m width in each side of the motorway. The 3.0 m hard shoulders are separated from the inside lanes by side strips 0.75 m in width which are also next to the outside lanes. - Sub-grade preparation (e.g. ground compaction) - groundworks - Road marking - Drainage measures (drains, gullies etc.) <u>Motorway construction</u> *Asphalt constructions:* *Pavement with mastic asphalt (MA)* - A: 0% recycled material for all layers - B: 0% recycled material for other layers - 100% recycled material for frost blanket - Maintenance scenario A: 2x replacement of surface layer – 1x replacement of binder layer - Maintenance scenario B: 2x replacement of surface layer – 2x replacement of binder layer *Porous asphalt (PA)surface layers* - A: 0% recycled material for all layers - B: 0% recycled material for other layers - 100% recycled material for frost blanket Maintenance scenario A: 3x replacement of surface layer – 1 x replacement of binder layer - Maintenance scenario B: 4.3x replacement of surface layer – 1 x replacement of binder layer *Concrete constructions: pavement with textured surface (tC) or exposed aggregate concrete surface layer (EAC)* - A: 0% recycled material for all layers, CEM I for concrete surface layer - B: 0% recycled material, CEM I for surface layer 100% recycled material for frost blanket - C: 0% recycled material for all layers, CEM III for surface concrete layer - Maintenance scenario A: 2x complete renovation of joints – 5% repair of broken edges and corners – 1% lifting and fixing of slabs, 1% replacement of slabs - Maintenance scenario B: 3x complete renovation of joints – 20% repair of broken edges and corners – 3% lifting and fixing of slabs, 3% replacement of slabs <u>Use scenario</u> A: Standard fuel consumption B. 0.5% fuel savings C: 2% fuel savings D. 10% fuel savings for heavy goods vehicles	
Assumptions (e.g. allocation)	LCA only covers standard road cases, whereas the choice of a suitable and ecological construction method often depends strongly on local circumstances	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase**	Data on asphalt production, curing agents and concrete pavement, production methods (Ecoinvent) Data on materials and machines (Milachowski et al., 2010) and information from the Confederation of German Construction Industry Data on fuel consumption: European average of 0.286 kg/km diesel for heavy goods vehicles and, for cars, 0.0125 kg/km diesel or 0.0536 kg/km petrol (Spielmann et al., 2004)	S_{DATA} = (5+3+1)/3= 3

5. Maintenance and operation phase **6. End of Life phase**		
Calculation methodology/ programme	SimaPro	
Impact assessment categories/methods	Impact categories (CML, 2001) - Global warming potential (GWP) (classification A) - Ozone depletion potential (ODP) - Photochemical ozone creation potential (POCP) (classification B) - Acidification potential (AP) (classification B) - Eutrophication potential (EP) (classification B) The impact categories are only given in equivalents and are not normalized for comparison	$S_{IMPACTS}$ = 5
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	<u>Motorway construction</u> The potential environmental impact originates essentially in the materials, especially the energy-intensive production of cement and asphalt (between 57 and 66% in scenario A). The use of 100% recycled material for the frost blanket reduces the potential impact by amounts of 10 (ODP) and 31% (EP) <u>Use and maintenance</u> The impact reduction potential for maintenance measures in scenario A (minimum maintenance) compared to scenario B (maximum maintenance) lies between 20 and 60% depending on the impact category. The largest potential impact reduction lies in lowering fuel consumption (from 0.5% of GWP in the full life cycle where the fuel consumption is reduced by 0.5% to 2% of GWP in the full life cycle where the fuel consumption is reduced by 2% for all vehicles. When the fuel consumption is reduced by 10% for heavy vehicles the total emission of GHG during the full life cycle is reduced by 4.7%). These are merely examples of relationships between fuel consumption and reduction of GWP. The fuel consumption can be reduced by 5 to 20% when the road surface is optimized. The main reasons are reduced unevenness and increased stiffness of the road. For maintenance seen in isolation, the reduction potential is 30% for GWP when optimal maintenance is done. It is also stressed that motorway pavement maintenance is reduced significantly for concrete pavements compared to asphalt pavements. No calculations and data about noise are given but it is mentioned that asphalt has a positive effect on noise reduction compared to concrete.	S_{OUTC} = 5
Strengthens and weakness of the whole study, general comments	Different scenario are evaluated	$S_{ROBUSTN}$ = 1
Subject to independent review?	University Report prepared by Centre for building Materials, technische universität München, Germany in behalf of EU PAVE	S_{REVIEW} =1
		20

		Scoring
Authors	Carlson A.	
Year	2011	
Title	Life cycle assessment of roads and pavements. Studies made in Europe	
Reference	VTI rapport 736°	
Type of study	LCA review The survey of life cycle assessment studies of roads and pavements made in Europe is a report in sub-project 3 (SP3) in the MIRIAM project "Models for rolling resistance In Road Infrastructure Asset Management systems" (12 partners from Europe and USA). The report is limited to EU studies that can be considered the most relevant since the mid-1990s	S_{SCOPE} = 5
Scope	The scope of the single studies are: - Häkkinen & Mäkelä: analysis of the environmental impact of concrete and asphalt road pavements - Mroueh et al.: LCA of alternative road and earthwork construction. Case studies were made of using different industrial by-products in road and earth constructions - Stripple: comparison of the life cycle phases of two asphalt pavements and one concrete pavement - Hoang et al.: comparison of two different highway sections; one with asphalt concrete and one with reinforced concrete - Olsson et al.: assessment of two road constructions, one with natural aggregate only and one with municipal solid waste (MSW) incineration bottom ash in the sub-base layer - Birgisdóttir et al.: analysis of two different disposal methods of bottom ash from incineration of municipal solid waste were compared: 1. road construction (sub-base) 2. landfill. The focus is on the leakage to the soil - Huang et al.: LCA of a asphalt paving where natural aggregates are replaced with waste glass,	

	MSWI bottom ash and recycled asphalt pavements - Sayagh et al.: to assess three different pavement structures, two with classical material, asphalt and concrete, and one where blast furnace slag (BFS) - ECRPD: to evaluate the energy conservation in pavement manufacture and placement, i.e. low energy pavement materials and pavement maintenance on existing roads	
Functional unit	11 LCA of roads and pavements are studied in the report. The functional units from the publications are: - Häkkinen & Mäkelä: 1 km motorway, 50 years (in Tampere, Finland) - Mroueh et al.: 1 km road, 50 years - Stripple: 1 km road, 40 years - Chappat & Bilal: 1 m² pavement, 30 years (20 different road pavement techniques, in France) - Hoang et al.: 1 km highway, 30 years (in France) - Olsson et al.: 1 km road (in the Stockholm region in Sweden) - Birgisdóttir et al.: 4,400 tonnes of ash in 1 km road, 100 years - Huang et al.: 30,000 m² asphalt surface (at London Heathrow Terminal-5, in UK) - Sayagh et al.: 1 km road, 30 years - ECRPD: 1 km road, 4 roads (motorway, dual carriage way, wide single carriage way and single carriage way). 25 years (in 6 countries)	
System boundaries (stages and process cut-off)	- 9 studies include the road construction phase (of the pavement) - 4 studies include earthworks - 4 studies include the use phase (incl. daily traffic) - 7 studies include maintenance	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	The studies assessed are: - Häkkinen & Mäkelä from 1996 - Mroueh et al. from 2001 - Stripple from 2001 - Chappat & Bilal from 2003 - Hoang et al. from 2005 - Olsson et al. from 2006 - Birgisdóttir et al. from 2007 - Huang et al. from 2009 - Sayagh et al. from 2010 - ECRPD from 2010	S_{DATA} = 3
Calculation methodology/ programme	Project specific	
Impact assessment categories/methods	The 11 studies assessed in this report have considered varying potential environmental impacts. These are the full list of categories: Process energy (assessed in all 10 studies) - CO_2(assessed in all 10 studies) - NO_X - SO_X – CO – VOC – Particles - Other (heavy metals, waste, resource demand, CH_4, N_2O, HC etc.) The impact categories in the study are only given in equivalents and are not normalized for comparison.	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	A conclusion of this report is that it is impossible to perform straightforward comparisons of the results in LCA papers due to the differences in approach, functional units, analysis periods, system boundaries, regional differences, difference in input data etc. The (main) results from the individual studies addressed were: - Häkkinen & Mäkelä: The study includes the use phase (daily traffic from 20,000 vehicles). The largest potential environmental impact comes from the use phase traffic emission during the analysis period amounted to 2 orders of magnitude compared to all of the other stages in the life cycle). The second largest potential environmental impacts are caused by the use of cement for concrete pavements and bitumen for the asphalt pavements, the manufacturing and the maintenance operations. No recommendation can be given concerning the most optimal material from an environmental point of view. - Mroueh et al.: Includes industrial by-products (such as coal ash, crushed concrete waste and granulated blast-furnace slag) which are compared to natural aggregates. The energy use and CO2 emissions of the studied life cycle stages for each road construction alternative were very small in comparison with traffic, 0.1–0.2% for energy and 0.8–1.8% for CO2 The second largest phase is production and transportation of materials used in road construction. - Stripple: the energy use of a traffic volume of 5,000 vehicles per day was estimated in order to relate the energy use of the other life cycle stages of the road. The comparison showed	S_{OUTC} = 5

	that the calculated energy use of construction, operation and maintenance was between 10-12% of the estimated traffic energy The second largest parameter is energy consumption for the operation of the road (street lightning and traffic signals. Regarding the emission of CO_2, NOx and SO2 the construction of the road is the main contributor. - Chapat & Bilal: The study includes the use phase including traffic. The direct traffic energy and the GHG emissions over 30 years exceed the energy for construction and maintenance between 10 and 345 times, depending on light or heavy traffic. Description of the contribution made by 20 different road construction techniques regarding pavement, on energy use and GHG emission. Different traffic classes describing the number of light and heavy duty vehicles per day was analysed. The paper describes advantages by using bitumen emulsion and high modulus mixes due to the fact the energy consumption can be managed efficiently during the production and construction phases and the GHG emission can be decreased. Another conclusion is that the use of recycled material may save natural aggregates and transport. The pavement which resulted in the largest energy consumption and GHG emissions was reinforced cement concrete pavement followed by undowelled cement concrete pavement as compared to three alternatives with special hydraulic binder and cold mix asphalt, which present lowest energy use and GHG emissions. Hoang et al.: The use phase is not included. It is concluded that the reinforced concrete highway section consumes 40% more energy and emits 3 times more CO_2 than the asphalt concrete highway section. For the reinforced concrete road the cement and steel works are the main contributors. For the asphalt concrete the main contributors are hot mix production and materials transportation. - Olsson et al.: The use phase is not included. The paper concludes that reused and/or recycled materials leads to less energy use and energy-derived emissions. With MSW bottom ash the leaching of certain metals from the road was found to be larger. The major energy use is due to production of materials and the disposal stage, while the metals leach during the use phase. - Birgisdóttir et al.: The paper concludes that there is no significant difference of the two disposal methods from an environmental point of view. However, for human toxicity in soil and environmental toxicity in water the alternative of using bottom ash in road construction has an higher impact compared to landfilling the bottom ash. - Huang et al.: The production of hot mix asphalt and bitumen is the most energy intensive processes and also responsible for the largest emissions. The main aim was to calibrate an LCA model. - Sayagh et al.: The concrete road gave rise to the highest potential environmental impacts concerning GWP, acidification and eutrophication. The road with blast furnace slags caused the highest impacts in photochemical ozone formation and ecotoxicity, whereas asphalt pavement had the highest toxic potential. - ECRPD: The production of asphalt mixtures and their components constitute 90% of the energy consumed and emissions in total. The only deviation is that N_2O primarily derives from the operation phase. - Re-ROAD: The aim of this publication is to evaluate the end-of-life strategies for asphalt road infrastructures, mainly by evaluating strategies for recycling of asphalt. At the time of writing, the study was not finished.	
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 3
Subject to independent review?	Internal peer review was performed on 28 November 2011 by U. Hammarström and R. Karlsson. A. Carlson has made alterations to the final manuscript of the report. M. Göthe-Lundgren, VTI, examined and approved the report for publication on 2 December 2011	S_{REVIEW} = 3
		20

		Scoring
Authors	Santero N.J., Masanet E. and Horvath A.	
Year	2011a	
Title	Life-cycle assessment of pavements. Part I: Critical review	
Reference	Resources, Conservation and Recycling 55, pp. 801–809	
Type of study		S_{SCOPE} = 5
Scope	Evaluating the current status of LCA as applied to pavements, providing critical commentary on the strengths and weaknesses of the body of work, and developing future research directions	

	Review of 15 studies representing the published pavement LCA and LCI works as of 2010. Excluded from this review were works focusing solely on recycled materials use in pavements.	
Functional unit	Description of the functional unit of each reviewed paper	
System boundaries (stages and process cut-off)	In the reviewed LCAs: - Materials extraction and production is the only component captured by each paper. Material transportation is less studied (in 9 LCAs). Onsite equipment used in the construction of the pavement is accounted for in most of the studies, but the consequential delay caused to traffic is commonly omitted, even though it has the potential to seriously influence the overall life-cycle impacts (Santero and Horvath, 2009). Only three consider traffic delay, but two apply it only to initial construction (Chan, 2007; Huang et al., 2009) and the other only for maintenance (Häkkinen and Mäkelä, 1996). - Use phase is omitted from nearly all of the studies and it is the most significant shortfall from a system boundary perspective. The use phase of the pavement life cycle includes potentially influential components, including fuel consumption attributed to pavement roughness and structure, the urban heat island effect, radiative forcing, concrete carbonation, and leachate. Häkkinen and Mäkelä (1996) and Treloar et al. (2004) include fuel consumption and emissions from the traffic over the pavement, but use absolute values that reflect the total traffic rather than values that are isolated to the pavement's actual contribution. These values are helpful in understanding the impact of pavements relative to other impacts, but should not be wholly attributed to the pavement life cycle. **A pavement and its properties are only responsible for a fraction of the vehicle fuel consumption, namely those associated with its structural characteristics and surface texture.** Albedo-related environmental impacts (i.e. urban heat island and radiative forcing) are another component not discussed in the current literature - Although included in two-thirds of LCA studies, pavement maintenance is a far more complicated than is commonly portrayed. Accurately forecasting future maintenance activities (including rehabilitation) continues to be a challenging task. A combination of mechanistic empirical models and prescribed agency schedules offer a realistic forecast of the timing and intensity of future activities. Conversely, the maintenance phase in existing pavement LCAs is generally structured as a series of simple procedures that are repetitively carried out over the service life. **The maintenance phase has the potential to be a significant contributor to the overall environmental impact**	
Assumptions (e.g. allocation)	Environmental impacts of bitumen need to be allocated amongst a multitude of petroleum products, such as gasoline, diesel, and plastic As a hydrocarbon, bitumen has a certain amount of feedstock (or inherent) energy associated with it. By ISO standards, this chemical energy needs be included in any energy assessment (ISO, 2006b). There is active debate amongst the pavement LCA research community regarding the appropriate accounting technique. A 2010 workshop aimed at resolving such pavement LCA-related issues concluded that bitumen's feedstock energy is fundamentally different from embodied energy and thus should be treated differently from that of consumed energy (UCPRC, 2010). The workshop outcomes recommend that it be reported separately. The feedstock energy in bitumen, reported to be 40.2 MJ/kg (Garg et al., 2006), is over 6 times the maximum energy factor of bitumen production, making the exclusion or inclusion of this energy pivotal decision within a pavement LCA study	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Data for cement, for which the literature shows an energy intensity range of 4.6–7.3 MJ/kg of cement, and for bitumen, for which the range is 0.70–6.0 MJ/kg (Stammer and Stodosky, 1995; Häkkinen and Mäkelä, 1996; Berthiaume and Bouchard, 1999; Stripple, 2001; Athena Institute, 2006; Marceau et al. 2006; Carniege Mellon University, 2010) Wide variation in published factors is underlined and difficulty in establishing a single global factor. A sensitivity and uncertainty analyses for cement and bitumen, pavement structure, rolling resistance factors, carbonation rates, traffic delay are suggested	S_{DATA} = 3
Calculation methodology/ programme		
Impact assessment categories/methods	- In existing pavement LCAs, energy consumption is the most used metric for the evaluation of the environmental performance of a pavement. 9 studies added an inventory of various conventional air pollutants (e.g., SO2, NOX, CO, particulate matter), and another 10 add GHG. 4 studies report environmental impacts not associated with energy consumption or air emissions, including nitrogen releases into water, hazardous waste generation, heavy metal releases, and other environmental indicators. - The focus on energy consumption and, to a lesser degree, conventional air pollutant and GHG emissions promotes a disproportionate amount of attention onto only a few environmental metrics. Water consumption, toxic releases, land use, and other indicators may be equally pressing environmental concerns	$S_{IMPACTS}$ = 3

	- Each LCA study includes either energy consumption or GHGs. 3 of the 15 studies go a step further by conducting a quasi-impact assessment through the use of subjective weighting systems based on expert rankings, ecoscarcity models (Häkkinen T. and Mäkele K., 1996), or monetary impact (Mroueh et al., 2000).	
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	- Inconsistencies in the functional unit, system boundaries, data quality, and environmental metrics have created a situation where the results of different studies are largely incompatible and incomparable to one another, essentially making it impossible to aggregate the results and draw any broad conclusions - There are also many omitted components (many from the use phase of the pavement life cycle) that are not considered in the energy calculations, many of which have potentially large life-cycle impacts (Santero and Horvath, 2009). Even if the energy balance is decidedly in favor of one pavement type or another, there are still unresolved environmental issues, such as GHG emissions, criteria and toxic air emissions, and water consumption, which are arguably equally or even more pressing than energy consumption. - There are also problems in translating conclusions across regional boundaries. Differing electricity mixes, production practices, pavement designs, available materials, local maintenance practices, and other region-specific elements will create different results depending on the location under study. - By standardizing the functional unit (to the extent feasible), expanding system boundaries, improving data quality, and examining a larger array of environmental indicators, equitable assessments and comparisons can be performed with greater reliability	S_{OUTC} = 5
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 3
Subject to independent review?	Peer review	S_{REVIEW} = 3
		22

		Scoring
Authors	Yu B., Lu Q.	
Year	2012	
Title	Life cycle assessment of pavement: Methodology and case.	
Reference	Transportation Research Part D 17, pp. 380–388	
Type of study		S_{SCOPE} = 5
Scope	A LCA model is built to estimate the environmental implications of pavements using material, distribution, construction, congestion, usage, and end of life modules. A case study of 3 overlay systems with Portland cement concrete (PCC), hot mixture asphalt (HMA), and crack, seat and overlay (CSOL) for the rehabilitation of an old PCC pavement, is presented	
Functional unit	1 km of PCC, HMA and CSOL overlay systems [in each direction: inner paved shoulder width 1.2 m, 2*3.6 m and outsider paved shoulder 2.7 m]. An AADT of 70,000 vehicles, with 8% heavy traffic and a growth of 4% a year are supposed.	
System boundaries (stages and process cut-off)	Phases: - Materials - Distribution - Construction - Congestion - Usage - End of life Three replacement options frequently adopted in Florida are considered: - Remove and replace the 225 mm PCC pavement with 250 mm new PCC (the PCC option). Diamond grinding used to restore surface smoothness. Restoration every 16–17 years - Remove and replace the existing pavement with 225 mm HMA (the HMA option). Use a mill-and-fill (remove 45 mm HMA surface and replace the same depth of new HMA). Restoration every 16 years - Crack, seat, and overlay (the CSOL option). Crack and seat the existing PCC pavement and then overlay with 125 mm of HMA. Use the same mill-and-fill plan as the periodic rehabilitation strategy every 16 years EoL: RAP is accepted in paving mixtures with 10-50%substitution rates	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase**	<u>Material module</u>: reference model based on data from various sources including the Portland Cement Association (Marceau et al., 2007), the Swedish Environmental Research Institute (Stripple, 2001), and the Athena Institute (2006) <u>Distribution module</u>: GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in	S_{DATA} = (3+3+3)/3=3

3. Road construction phase
4. Use phase
5. Maintenance and operation phase
6. End of Life phase

Transportation, 2010) model with data for fuel and electricity production, truck transportation, tie and dowel bar production, and natural gas
Construction module: emission data for equipment from US EPA NONROAD 2008 model
Congestion module: QuickZone model for estimating the changes in traffic flow, traffic delay, and queue length. CO2 is calculated by the fuel consumptions (Emission Facts, 2005). Other vehicle emissions are calculated using US EPA's MOBILE 6.2 model
Usage module: miscellaneous models on traffic volume, fuel economy and roughness effect (Vision model). Increase in IRI reduces fuel economy, a relationship found by Amos (2006) in Missouri. A fuel consumption factor (FCF) is used to describe real fuel consumptions of vehicles driving on pavements with different IRIs:
FCF = 7:377 + 10-3 IRI + 0.993 for passenger cars
FCF = 2:163 + 10-2 IRI +0.953 for trucks
For albedo, Akbari et al. (2008) estimated that for every square meter, 2.55 kg of emitted CO_2 is offset for every 0.01 increase in albedo:
$\Delta mCO2 = 100*C*A* \Delta\alpha$ where $\Delta mCO2$ is the mass equivalents of CO2 mitigated (kg), C is the CO2 offset constant (kg CO_2/m^2), A is the area of pavement (m2) and $\Delta\alpha$ is the change is albedo.
For carbonatation, a simplification of Fick's second law of diffusion is used (Lagerblad, 2006): $d=k*t^{1/2}$ where d is the depth of carbonation (mm), k is the rate factor ($mm/y^{1/2}$) and t is time (year).
End of life: mobile model

Calculation methodology/ programme

LCA model with material module, distrivution module, construction module, usage module and EOL module

Impact assessment categories/methods

- Energy (primary & feedstock)
- CO_2
- CH_4
- N_2O
- VOC
- NO_x
- CO
- PM10
- SO_x

$S_{IMPACTS}$ = 1

Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)

The energy consumed for 1 km of the PCC, HMA, and CSOL overlays are 61 10^3 GJ, 129 10^3 GJ, and 101 10^3 GJ. The energy consumptions for three scenarios are all dominated by material, congestion, and usage modules. If usage module is not considered, the energy consumptions for PCC, HMA, and CSOL options witness reductions of 40%, 50% and 44%.

Inventories associated with the alternatives.

Input-output		Energy (GJ) Primary	Energy (GJ) Feedstock	CO_2 (tonne)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
PCC	Material	12,709	NA	1219	659	4	111	2194	14,118	3168	1158
	Distribution	185	NA	14	16	0.3	5	17	8	2	4
	Construction	70	NA	4	0^a	negligible	23	291	133	14	8
	Congestion	11,274	NA	759	0^a	0^a	877	−2908	−27,414	116	1
	Usage	37,083	NA	1863	0^a	0^a	3057	1376	73,470	55	59
	EOL	100	NA	13	8	0.2	5	44	17	4	3
HMA	Material	13,958	39,034	930	2247	1	205	1994	199	64	879
	Distribution	245	NA	19	21	0.4	7	22	11	3	5
	Construction	97	NA	54	0^a	negligible	30	390	172	30	11
	Congestion	10,792	NA	726	0^a	0^a	1103	−1625	−15,291	67	3
	Usage	64,688	NA	4964	0^a	0^a	4814	5343	115,670	85	92
	EOL	143	NA	37	7	0.14	22	297	168	22	8
CSOL	Material	9539	26,868	836	1535	1	140	1362	136	44	60
	Distribution	118	NA	9	10		3	11	5	1	2
	Construction	74	NA	41	0^a	negligible	23	312	143	24	9
	Congestion	8190	NA	551	0^a	0^a	1104	−1625	−15,291	67	3
	Usage	56,419	NA	4340	0^a	0^a	4767	5227	115,215	86	92
	EOL	79	NA	21	4	0.1	12	165	93	12	5

Note: 0^a: the item is not within outputs of the models and a zero value is assigned although this does not influence the results significantly because CO_2 emissions are three orders bigger than other GHGs, CO_2, CH_4, and N_2O.

The PCC option is most environmental friendly, but uncertainties exist GHG is dominated by material, congestion, and usage modules for the three pavement rehabilitation. Carbonation and albedo gives credit to the PCC option. CO_2 dominates the GHG emissions.

IRI increase rate is a factor that would influence the traffic related energy consumption. At a 2% higher IRI development, the additional fuel consumption is 2%, 1.4%, 1.6% for the PCC, HMA, and CSOL options. At a 4% higher IRI development rate, the additional fuel consumption is 4%, 2.7%, 3.2% for the PCC, HMA, and CSOL options.

In conclusion, materials, congestion, and usage are the three major sources of energy consumptions and air pollutant emissions in the usage module. Traffic related fuel consumption is emerges as very sensitive to traffic growth and fuel economy improvements. Fuel consumption basically increases linearly with the traffic growth rate.

S_{OUTC} = 5

Strengthens and weakness of the whole study, general comments

Based on different modules

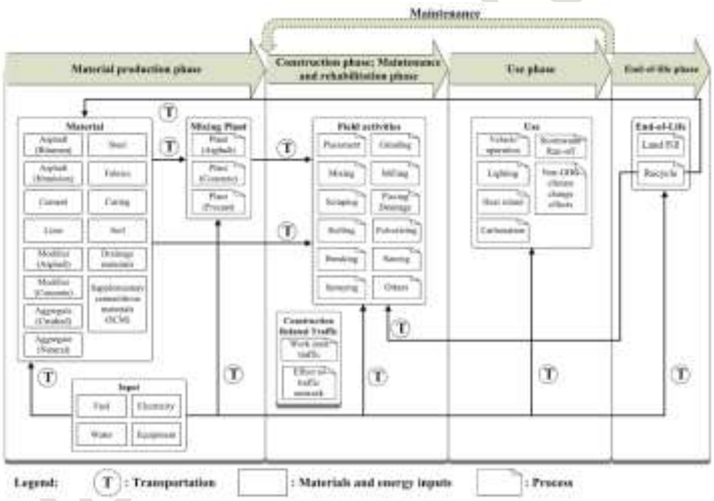
$S_{ROBUSTN}$ = 3

Subject to independent review?

Peer review

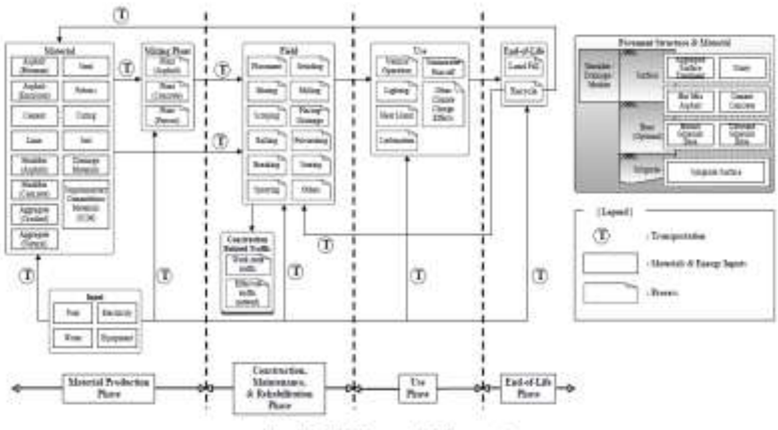
S_{REVIEW} = 3

20

		Scoring
Authors	Wang T., Lee I-S., Kendall, Harvey, Lee E-B, Kim C.	
Year	2012a	
Title	Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance	
Reference	Journal of Cleaner Production 33, 86-96	
Type of study	According to ISO 14040 and PAS 2050:2011	S_{SCOPE} =
Scope	The aim of the paper is to evaluate the potential energy and GHG savings from treating distressed pavements by means of <u>maintenance and restoration (M&R) strategies</u> compared to routine maintenance, considering both the materials production and construction phases with the use phase. The paper describes a larger model, MOVES, which has been developed by the authors together through a large research programme. The model evaluates changes in fuel economy caused by changing rolling resistance of the road. Examples are discussed in the paper of selected pavement surfaces, traffic growth etc.	5
Functional unit	There are several functional unit expressed as 4 different case studies (4 flat rural California road segments, applicable to highway network into similar sections): - KER-5: 16.1 km of road, 2 lanes, asphalt as surface layer and construction type: CAPM with two types of asphalt overlay. 34,000 AADT, 35% trucks, during 5 years - BUT-70: 8 km of road, 4 lanes and construction type: CAPM, asphalt overlay. 3,200 AADT, 15% trucks, during 5 years - LA-5: 16.1 km road, 2 lanes. Surface type: concrete. Construction type: CPR B. 86,000 AADT, 25% trucks, during 10 years - IMP-86: 8 km road, 2 lanes. Surface type: concrete. Construction type: CPR B. 11,200 AADT, 29% trucks, during 10 years  <u>Preservation strategies</u> - CAPM: Capital Preventive Maintenance asphalt overlay for existing asphalt pavement where the old surface is milled prior to placing a new surface. Two types of materials, dense-graded conventional hot mix asphalt (HMA) and gap-graded rubberized hot mix asphalt (RHMA) are considered - CPR: Concrete Pavement Restoration including 3% slab replacement and a full lane diamond grinding (CPR B). Two types of material, high early strength Portland cement concrete (Type III PCC) and calcium sulpho-aluminate (CSA) cement concrete are considered	
System boundaries (stages and process cut-off)	Phases: - Material production phase - Construction phase (including maintenance and rehabilitation phase and transportation phase) - Use phase Excluded from the study: - routine maintenance and EOL, because they are assumed to be the same between different scenarios <u>Transport from and to the construction site</u>: HMA: 72 km and 72 km; RAP: 0 km, Concrete: 32 km and 24 km	
Assumptions (e.g. allocation)	This study assumes nighttime construction, which is typical in California, with a 9-h partial lane closures. Given the rural location of the case studies and nighttime construction scheduling, no work zone traffic delay was considered and no construction delay as well (sufficient crew/machines)	
Data sources and quality	Multiple data sources for each material were included in the analysis. These data sources are	S_{DATA} =

<table>
<tr><td>1. Raw materials production phase
2. Production phase
3. Road construction phase
4. Use phase
5. Maintenance and operation phase
6. End of Life phase</td><td>from published LCI databases and other LCA reports, including the pavement LCI produced by Stripple et al. in Sweden (Stripple, 1998), the asphalt inventory produced by the Athena Institute in Canada (Athena Institute, 2006), EcoInvent (Swiss Centre for Life Cycle Inventories, 2011), the U.S. Life Cycle Inventory (USLCI) produced by the National Renewable Energy Laboratory (National Renewable Energy Laboratory, 2011), the cement LCI study by the Portland Cement Association (PCA) (Marceau et al., 2006), and some other data sources.</td><td rowspan="2">(3+3+3) = 3</td></tr>
<tr><td>Calculation methodology/ programme</td><td>Assessment method developed in the study, part of its purpose</td></tr>
<tr><td>Impact assessment categories/methods</td><td>- GHG
- Energy consumption
The impact categories in the study are only given in equivalents and are not normalized for comparison.</td><td>$S_{IMPACTS}$ = 1</td></tr>
<tr><td>Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)</td><td>
The results in the paper are presented as impacts and resource consumption compared to a reference scenario “Do Nothing” (only the minimum level of maintenance work performed annually to keep the current pavement condition deteriorating at a very slow rate). The results are provided for 0% and 3% traffic growth combined with either a “less smooth rehab” (brings down the IRI to 1 m/km) and a “smooth rehab” (1.67 m/km).
The study concludes that large savings in GHG emissions and fuel consumption are obtained when the roughness of the road is reduced. The improvement potential is approx. 2.5% of the fuel consumption during the full life cycle of the road (in this case 16.1 km long road). The authors conclude that the GHG emission closely resembles the fuel consumption in the use stage.
Example calculations show that the feedstock energy of materials can be up to three times as high as the energy used during materials production. A deeper explanation of this statement is not provided in the paper.
Table 1. Life cycle energy and GHG saving compared to Do Nothing over the analysis period under 0% traffic growth with Smooth rehab strategy
<table>
<tr><th>Case study (analysis period)</th><th>Material</th><th>Feedstock energy (10^6MJ)</th><th>Material production (Average value, 10^6MJ)</th><th>Construction (10^6MJ)</th><th>Use (10^6MJ)</th><th>Total energy saving (10^6MJ)</th><th>GHG reduction (Metric tonCO$_2$-e)</th></tr>
<tr><td>KER-5 (5 years)</td><td>HMA</td><td>−33</td><td>−20</td><td>−7.0</td><td>100</td><td>74.7</td><td>5,283</td></tr>
<tr><td></td><td>RHMA</td><td>−49</td><td>−18</td><td>−5.4</td><td>100</td><td>77.9</td><td>5,733</td></tr>
<tr><td>BUT-70 (5 years)</td><td>HMA</td><td>−17</td><td>−9.8</td><td>−3.6</td><td>4.7</td><td>−8.7</td><td>−695</td></tr>
<tr><td></td><td>RHMA</td><td>−24</td><td>−9.1</td><td>−2.7</td><td>4.7</td><td>−7.1</td><td>−471</td></tr>
<tr><td>LA-5 (10 years)</td><td>Type III cement</td><td>0</td><td>−9.4</td><td>−4.4</td><td>550</td><td>530</td><td>18,136</td></tr>
<tr><td></td><td>CSA cement</td><td>0</td><td>−7.3</td><td>−4.4</td><td>550</td><td>540</td><td>18,471</td></tr>
<tr><td>IMP-86 (10 years)</td><td>Type III cement</td><td>0</td><td>−4.7</td><td>−2.2</td><td>29</td><td>23</td><td>1,377</td></tr>
<tr><td></td><td>CSA cement</td><td>0</td><td>−3.6</td><td>−2.2</td><td>29</td><td>24</td><td>1,544</td></tr>
</table>
Overall calculation results are provided in the report without indications of exact magnitude of the impacts and resource consumptions. Examples are:
- The energy consumption in the materials production phase is very small compared to the use phase with high traffic volume (KER5 and LA-5). Energy savings in the use phase can outweigh the energy consumption in the materials and construction phases.
- In the low volume traffic cases (BUT-70 and IMP-86), the materials production phase gains increased importance
- A 10% reduction in the rolling resistance can generally lead to 1-2 % improvement in fuel economy.
Regarding materials it is mentioned that no comparisons can be made due to the inherent data variability caused by different system boundaries etc. Nevertheless, it is shown in the results that asphalt contains a larger share of feedstock energy which is bound in the road construction. Furthermore, the potential environmental impact caused by the use of materials for flexible roads are higher than for concrete roads (designed to carry approximately the same AADT).
</td><td>S_{OUTC} = 5</td></tr>
<tr><td>Strengthens and weakness of the whole study, general comments</td><td>Sensitivity analyses based on different sources of inventory data for the materials production phase are included</td><td>$S_{ROBUSTN}$ = 5</td></tr>
<tr><td>Subject to independent review?</td><td>Peer review paper</td><td>S_{REVIEW} = 3</td></tr>
<tr><td></td><td></td><td>22</td></tr>
</table>

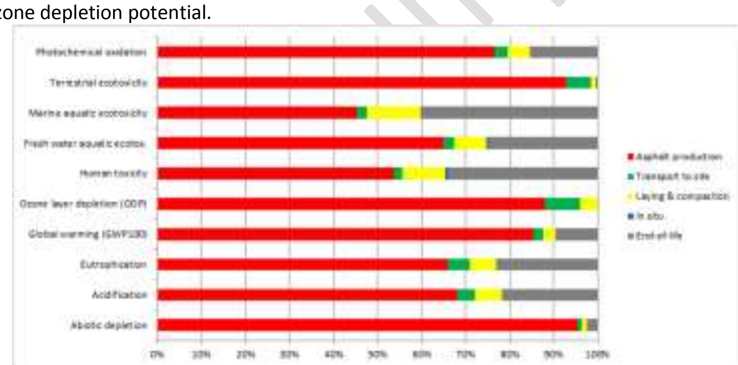
		Scoring
Authors	Wang T., Lee I-S., Kendall, Harvey, Lee E-B. and Kim C.	
Year	2012b	
Title	UCPRC Life Cycle Assessment methodology and Initial Case Study on Energy Consumption and GHG Emissions for Pavement Research Preservation Treatment with Different Rolling Resistance	
Reference	Research Report: UCPRC-RR-2012-02 at the Pavement Research Center at the University of California	
Type of study	According to ISO 14040 and PAS 2050:2011	S_{SCOPE} =

Scope	The aim of the study is to develop an LCA methodology (methods, approach, tools and models) to calculate the net life cycle impact of the pavement preservation treatments. In this paper the preliminary developed methodology are on four example case studies which each involve the most typical Caltrans pavement preservation treatments and materials used for those treatments. This report first presents the methods, approach, tools, and models developed to calculate the net life cycle impact of the preservation treatment for the selected pavement M&R strategies. The results of the case studies also provide a preliminary indication of the relative effect on the outcome of the following variables: - Automobile and truck traffic levels - Constructed smoothness of the M&R treatment - Material used for the M&R treatment (type of concrete or asphalt)	5
Functional unit	There are several functional unit expressed as 4 different case studies (4 flat rural California road segments, applicable to highway network into similar sections): - KER-5: 16.1 km of road, 2 lanes, asphalt as surface layer and construction type: CAPM with two types of asphalt overlay. 34,000 AADT, 35% trucks, during 5 years - BUT-70: 8 km of road, 4 lanes and construction type: CAPM, asphalt overlay. 3,200 AADT, 15% trucks, during 5 years - LA-5: 16.1 km road, 2 lanes. Surface type: concrete. Construction type: CPR B. 86,000 AADT, 25% trucks, during 10 years - IMP-86: 8 km road, 2 lanes. Surface type: concrete. Construction type: CPR B. 11,200 AADT, 29% trucks, during 10 years <u>Preservation strategies</u> - CAPM: Capital Preventive Maintenance asphalt overlay for existing asphalt pavement where the old surface is milled prior to placing a new surface. Two types of materials, dense-graded conventional hot mix asphalt (HMA) and gap-graded rubberized hot mix asphalt (RHMA) are considered - CPR: Concrete Pavement Restoration including 3% slab replacement and a full lane diamond grinding (CPR B). Two types of material, high early strength Portland cement concrete (Type III PCC) and calcium sulpho-aluminate (CSA) cement concrete are considered For both pavement preservation strategies (CAPM treatments: CPR and CPR B), the existing pavement was assumed to remain otherwise unaltered. The analysis periods were specifically selected to be different for the asphalt and concrete treatments and the results were not annualized to avoid direct comparison between them.	
System boundaries (stages and process cut-off)	Phases: - Material production (raw materials extraction, production/refining, mixing processes for asphalt and concrete) - Construction phase (including maintenance and rehabilitation (M&R) phase and transportation phase) - Use phase  Figure 3.1: UCPRC Pavement LCA Framework. Excluded from the study: - Routine maintenance and EOL, because they are assumed to be the same between different scenarios - Traffic delay, because construction work was scheduled to be performed at night, and given the rural location of the case studies - Water and land use - Criteria pollutants and other Environmental impacts - Equipment manufacturing, roadway facilities installation and operation	

	- Equipment transport by truck, transport distance and traffic congestion - Heat islands and carbonation Since the results in this study are limited to an evaluation of the effects of pavement deterioration and maintenance, only the effect of these two factors have effect on fuel economy, have been included in the use phase (without consideration of vehicle damage, freight damage, or tire wear). This assumption is considered reasonable by the authors given the assumptions that pavement type, the effects of heat island, the non-GHG climate change effect from pavement albedo, roadway lighting, and carbonation will all remain the same, and therefore they are not expected to differ among the alternatives examined for each case study. Later in the process of developing the methodology should the albedo of the surface and the viscoelastic response of the pavement be included. Also EoL will be taken into consideration in the future	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	<u>LCI of the materials production phase (ISO 14040 and UCPRC Pavement LCA Guideline and U.S. EPA's Compilation of Air Pollutant Emissions Factors, Volume I:Stationary Point and Area Sources)</u> (material acquisition; material production or processing prior to delivery to the mixing plant; mixing processes at the mixing plants; and material transport between the mixing plant and construction site by truck operation) Electricity inventory data were taken from several LCA and LCI sources; Ecoinvent (2011), Stripple (2001), Häkkinen (1996) and Athena (2006). Fuel inventory data were taken from several LCA and LCI sources; Ecoinvent (2011), Stripple (2001), Häkkinen (1996) and Athena (2006). Crushed aggregate inventory data were taken from several LCA and LCI sources; Ecoinvent (2011), Stripple (2001), Häkkinen (1996), Athena (2006) and PCA (2006). Natural aggregate inventory data were taken from several LCA and LCI sources; Ecoinvent (2011), Stripple (2001), Häkkinen (1996), Athena (2006) and PCA (2006). Bitumen inventory data were taken from several LCA and LCI sources; Ecoinvent (2011), Stripple (2001), Häkkinen (1996), Athena (2006), Eurobitume (2011) and USLCI (2011). Crumb rubber modifier inventory data were taken from Corti (2004). Extender oil inventory data were taken from Ecoinvent (2011). Recycled asphalt pavement inventory data were taken from Athena (2006). HMA mixing plant inventory data were taken from Stripple (2001), and Athena (2006). Cement inventory data were taken from several LCA and LCI sources; Ecoinvent (2011), Stripple (2001), Häkkinen (1996), Athena (2006) and PCA (2006). Concrete admixture inventory data were taken from EFCA (2006). Dowel bar inventory data were taken from Word Steel Association (2011). Concrete mixing plant inventory data were taken from several LCA and LCI sources; Ecoinvent (2011), Athena (2006) and PCA (2006). A sensitivity analysis with respect to data source has been provided <u>LCI of the materials construction phase</u> <u>LCI of the materials use phase</u> Direct emission from on-road hauling trucks was calculated with the EMFAC model from CARB (2006). Direct emission from construction equipment was calculated with the OFFROAD model from CARB (2007). The software CA4PRS was used to quantify the total operation hours of construction equipment. The relationship between surface characteristics and rolling resistance was calculated with the use of HDM-4 from PIARC. Vehicle fuel consumption and emission was calculated using MOVES from U.S. EPA (ver. 2010a)	S_{DATA} =(3+3+3)/3=3
Calculation methodology/ programme	The UCPRC pavement LCA model has been developed. Sub-models use other models as EMFAC, OFFROAD, CA4PRS and MOVES	
Impact assessment categories/methods	- Energy consumption - GWP (IPCC, 2007) (classification A)	$S_{IMPACTS}$ = 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	**Asphalt concrete production and construction** The main energy consumption is in asphalt production are mixing plant operations (when feedstock is excluded); Hot-Mix Asphalt (HMA): 40-50 % and Rubberized-HMA (RHMA): 27-43% and binder production HMA: 12-35 % and RHMA: 30-65%. The feedstock energy in asphalt can be up to 3 times higher than the energy actually used in the material production. The main contributors to GHG emission in asphalt production are mixing plant operations; HMA: 45-65 % and RHMA: 35-60% and binder production HMA: 15-30 % and RHMA: 25-50%. In the construction phase, the transport of HMA and RHMA accounts for approx. 55 % of both energy consumption and GHG emissions. **Cement concrete production and construction** Material production using type III Portland cement accounts for 54-57 % of the energy consumption in material production and construction phase, and 37-45 % using calcium sulfoalumite cement (CSA). The rest are roughly split between construction transport and construction equipment operation.	S_{OUTC} = 5

	Material production using type III Portland cement accounts for 60-80 % of GHG emissions in material production and construction phase, and 50-75 % using calcium sulfoalumite cement (CSA). The rest are roughly split between construction transport and construction equipment operation. Binder accounts for 70-75% of energy consumption and 84-92 % of GHG emission from production of type III cement (the rest are from chemicals admixtures) and approx. 98-100 % for both impacts in production of CSA cement. **Use phase** Optimal pavement maintenance can result in net reduction in GHG emissions and energy use for high-volume routes of 3,400-6,161 CO_2-eq. (44-80 10^6 MJ) over 5 years in KER-5 and 3,618-44,018 CO_2-e (57-610 10^6 MJ) over 10 years in LA-5 depending on annual traffic growth and initial smoothness. Reduction of traffic volume has a much higher impact than pavement maintenance and reduction in fleet fuel economy. Nevertheless, the pavement maintenance can result in significant net reductions of GHG emissions and energy for high volume roads. The net savings depends on the number of vehicles using the road.	
Strengthens and weakness of the whole study, general comments	Sensitivity analyses based on different sources of inventory data for the materials production phase are included	$S_{ROBUSTN}$ = 5
Subject to independent review?	University Report prepared for Division of Research and Innovation Office of Roadway Research and the MIRIAM project	S_{REVIEW}= 1
		22

		Scoring
Authors	Wayman M., Parry T., Andersson-Sköld Y., Raaberg J., Bergman R., Enell A. and Huang Y.	
Year	2012	
Title	Life Cycle Assessment of reclaimed asphalt.	
Reference	Re-Road project. Deliverable 3.4	
Type of study	According to ISO 14040	S_{SCOPE} = 3
Scope		
Functional unit	1 m^2 of single lane highway (thickness: surface 40 mm, binder 80 mm; base 100 mm; sub-base, unbound 150 mm) over a 60 year service life The baseline material is Stone Mastic Asphalt (SMA) 11S (aggregate size 0-11 mm) with polymer modified bitumen (PmB) 25/55-55A	
System boundaries (stages and process cut-off)	Phases: - Raw materials extraction, transport and storage - Asphalt production and delivery - Construction - Use (utilization of the pavement by road vehicles) - Maintenance - End of Life Scenario: A) only virgin asphalt in each bound course and only virgin aggregates in the sub-base B-K) degree of recycling (A, B, C, D), where A is the percentage of RA included in the surface course, B in the binder course, C in the base course and D in the sub base	
Assumptions (e.g. allocation)	The issue of allocation (ISO 14040) arises in relation to two main processes in the asphalt recycling life cycle. These are Bitumen production and Recycling of asphalt (closed-loop recycling requires particular consideration in order to allocate the benefits of recycling) In the case of bitumen production, there are two potential allocation solutions: the first uses mass and the second the economic value of the product. A combination of the two methods is used, allocation by mass is applied to crude oil refining and transport. Economic allocation is applied once crude oil reaches the refinery (allocation in mass would accentuate the impacts of bitumen and asphalt overall, thus any physical savings in bitumen achieved through recycling would realise more prominent benefits. By the same token, any adjustment in the economic value of bitumen may also result in changes though this would only occur if the price of bitumen changed relative to other crude oil fractions) For RA, since closed-loop recycling occurs, the need for allocation within the product system is avoided according to the Standard (ISO 14040). The benefits of utilising the recycled material are realised when RA displaces virgin material in new asphalt mixtures	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase**	Ecoinvent and other sources of information as: Raw materials acquisition and processing (Eurobitume, VTI 2008) Raw materials transport (ECRPD WP6) Asphalt production (converted from EAPA, 2007; Harder et al. 2008) Material transportation to the site (ECRPD WP6) Use (leaching: Birgisdottir et al., 2007 – dust Sjödin et al. 2010) Maintenance (EAPA, 2007) EoL (ECRPD WP6) Some primary data was available: mix designs and energy consumption at plant	S_{DATA} = (3+3+3)=3

6. End of Life phase		
Calculation methodology/ programme		
Impact assessment categories/methods	CML 2007 and EN 15804:2012 standard on the Sustainability of Construction Works. - Depletion of abiotic resources - Acidification (classification B) - Eutrophication (classification B) - Global warming (classification A) - Ozone depletion - Photochemical oxidation (classification B) In addition, four impact categories related to toxicity have been analysed (fresh water aquatic, marine aquatic, terrestrial and human), because of the potential leaching of RA from stockpiles or from the highway structure As an additional analysis (optional according to according to ISO 14040, a normalization is provided according to the total annual environmental loads in Western Europe per person in 1995 (each impact in the characterised system is divided by the total environmental load for that impact in 1995). When considering the normalised data, it should be considered that (a) different receptors (and environments) will have varying susceptibility to different impacts, and (b) normalisation is based on data generated in 1995 and has not since been refreshed	$S_{IMPACTS}$ = 5
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	Many of the benefits stem from the fact that extraction and refining of bitumen is particularly impacting and the properties of bitumen are preserved in recycling; thus extraction and refining are avoided for the fraction of bitumen that is preserved. Greater benefits are realised when higher rates of recycling are achieved (about 67% of asphalt is not yet recycled to bound courses). The EU production of asphalt for road paving is 331 Mt/y of production, therefore maximising recycling could realise close to a further million tonnes of GHG savings per year. Figure 1 indicates the relative importance of the different life cycle stages; asphalt production (incorporating raw material sourcing, transport and plant heating and mixing) is by far the most impacting stage. The most significant normalized environmental impacts of the recycled asphalt product system are marine aquatic ecotoxicity and abiotic depletion, and the least significant is ozone depletion potential.  *Fig. 1* Some additional benefit 1. if high specification aggregates (HSA), used for their skid resistance properties in the surface course, are preserved by surface-to surface course asphalt recycling. The results indicate that a small amount of recycling to a bound course is preferential to unbound recycling, due to the reduced requirement for virgin bitumen in the bound scenario. 2. To demonstrate the importance of minimising road transport, a "tipping point" analysis is provided to determine how much additional transport can be undertaken before all the benefits of recycling are neutralized. Depending on the impact category, the tipping points are just 17-102 km of additional transport for the low recycling scenario (just 15% to the surface course). 3. The research results were inconclusive with regards to potential hazardous substances arising in the utilisation or storage of RA. Past studies seemed to indicate that higher levels of hazardous substances (particularly organic compounds such as PAHs) are associated to the use of RA in comparison to natural aggregates and bitumen. However, the concentrations realised by experiments seemed to have very little significance within the chosen LCIA. 4. The results indicated that warm mixing has a substantial benefit, across most of the impact categories considered. The scale of the benefits were less than those achieved by a moderate level of recycling (15%); on average they were around one third in magnitude. The benefits of warm mixing can further be diminished by any additives used to achieve lower temperature mixing. In a similar way, the results indicated that the presence of moisture in RA material may also marginally deplete some of the benefits of recycling though not to the same extent as additives in warm mixing. This only applies where the moisture in RA material is greater	S_{OUTC} = 5

	than the levels that are found in natural aggregates used in asphalt. Adding 1% wax (m/m; binder fraction) reduces the beneficial impact of warm mixing significantly in relation to four impact categories: acidification, eutrophication, global warming and photochemical oxidation. 5. Data regarding the durability of pavements with or without recycled content remains frustratingly scarce. The limited data that could be gathered during the course of this study suggested recycled content had no effect on durability	
Strengthens and weakness of the whole study, general comments	Different scenario are evaluated	$S_{ROBUSTN}$ = 3
Subject to independent review?	FP7 EU research project report	S_{REVIEW} = 1
		20

		Scoring
Authors	Barandica J.M., Fernández-Sánchez G., Berzosa A., Delgado J.A. and Acosta F.J.	
Year	2013	
Title	Applying life cycle thinking to reduce greenhouse gas emissions from road projects.	
Reference	Journal of Cleaner Production 57 (2013), pp.79-91	
Type of study		S_{SCOPE} = 3
Scope	Evaluation of the GHG emission in road construction projects in a LCA perspective LCA review: there are almost no contributions which include all life cycle stages of an entire road construction project and usually certain aspects are omitted or underestimated. For example, the carbon balance associated with land use change, including the destruction of environmental systems or their reforestation, is not assessed in any studies	
Functional unit	1 km of built road. Life time is 50 years. Influence of road type, topography, length ・ Project 1: highway 30,36 km, 4 lanes. Material transport distance 16 km (min 5 – max 40) ・ Project 2: highway 9,7 km 2-4 lanes. Material transport distance 14 km (min 5 – max 40) ・ Project 3: highway 6.2 km 4 lanes. Material transport distance 16 km (min 5 -max 40) ・ Project 4: conventional road 29.2 km 2 lanes. Material transport dist. 16 km (min 5-max 40)	
System boundaries (stages and process cut-off)	Phases: - Extraction of raw materials and production - Construction - Use including carbonation of materials (concrete can absorb up to 3800 kg CO_2/m^3 in 100y) - Maintenance including restoration activities (CO_2 absorption of restored environmental systems) and operation of the road (street lighting, road cleaning etc.). Maintenance activities are: - road cleaning (monthly) - cleaning bushes/trees (twice per year) - Scheduled firm replenishment (every 9 years) - Replacement of road markings (once per year) Exclusion from the study: - Use phase because of the absence of a traffic model applicable to all roads - EoL	

	Scope and results of road project studies. (table below)	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Data on emissions related to off-road machinery, thermal and electrical energy sources. Data on fuel consumption and emission factors by means of EMEP Tier 3 methodology (EEA, 2009) Data on consumption of some equipment, machinery distance, fuel type and vehicle ageing carried out within the CLEAM research project (CLEAM, 2010) Regarding electric mixes, combination of national information on combustion emission factors of fuels and alternative sources (MITYC, 2010), and estimations of pre-combustion emissions (Hondo, 2000; White, 2000; Meier, 2002), using the calculation rules proposed by the national regulatory body (CNE, 2009). Creation of a database containing 80 materials, 105 construction machines, 42 energy sources, 8 electricity mixes, 80 categories of environmental systems, 10 types of waste and 21 transport vehicles used in road projects in Spain	S_{DATA} = (5+5+3) /3= 4.33
Calculation methodology/ programme	CO2NSTRUCT tool, a management information system	
Impact assessment categories/methods	- GWP 100 (IPCC2007) Land-use changes and evolution of resultant land uses have been assessed as variations of carbon sinks (estimation of emissions in LULUCF sector, IPCC (2003)). This task required a categorization in Spain in order to estimate the carbon sequestration capacity over time of the restored systems (Barandica et al., 2010).	$S_{IMPACTS}$ = 3
Conclusions (e.g. most important life lifecycle phases; most important	Total emissions vary from 8880 to 50,300 t CO2e/km, most of them related to road construction activities. The relative importance of maintenance is small in relation to construction (7.6-35.3% of the total). The contribution of other non-CO_2 gases is 6-8.5% of total emissions in construction	S_{OUTC} = 5

Scope and results of road project studies.

Authors	Year	Life-cycle stages								Gas species					Other aspects			Results
		Material extraction and production		Transport	Construction		Maintenance		End of life	CO_2	CH_4	N_2O	Shown as CO_2e	Others	Lifespan (years)	Land use and land-use change	Concrete carbonation	tCO_2e/km
		Pavement	Others		Earthworks	Roadway	Preservation	Repair										
Mroueh	2000	•		•	•	•		•					•		50			297–396
Stripple	2001	•	•	•	•	•	•	•		•	•	•		•	40		•	2000–2500
Nisbet et al.	2000	•		•		•				•	•				40			n/d
Park	2003	•	•	•	•	•	•	•	•				•	•	20			8940
Treloar	2004	•				•	•						•		40			1632
Athena	2006	•		•		•		•		•	•	•	•		50			400–1266
Birgisdóttir et al.	2006	•	•	•	•	•	•	•					•	•	100			1755
SUSCON	2006	•		•	•	•	•	•					•	•	50			940
Garrain and Vidal	2008	•		•		•							•		40			1320–3760
Huang et al.	2009a	•		•		•	•	•					•	•	15			853–900
Huang et al.	2009b	•		•				•	•				•	•	–			284[a]
Chang et al.	2010												•		–			n/d
White et al.	2010	•		•		•							•		–			128–587
Weiland and Muench	2010	•		•		•		•					•	•	50			0.124–0.331[c]
Milachowski et al.	2011	•		•	•	•		•					•	•	30			2214–3093[b]
Loijos	2011	•		•		•	•	•	•				•		40		•	404–6500
Cass and Mukherjee	2011	•		•	•	•							•		–			1956–3436[a,c]
Huang et al.	2012	•		•	•	•		•					•		25			897–9626
Melanta et al.	2012	•		•	•	•							•		20	•		38 785
CO2NSTRUCT	2011	•	•	•	•	•	•	•		•	•	•	•	•	50	•	•	8880–50 300

[a] Note that this study do not include the Construction stage, it is a rehabilitation project.
[b] Only counting road construction (1425–2821) and repair, traffic is not included in this value.
[c] A four lane road is assumed.

drivers to impacts - process/material; improvement options)	and 0.6-2% in maintenance.	

Table 1 Total emissions broken down by stages and gases, and emission per km of the analysed projects. All value are in tCO2e

Project	Emissions in Construction stage		Emissions in Maintenance stage		Total emissions	
	CO_2	Other GHG	CO_2	Other GHG	Project	Per km
1	36 200	28 000	70 100	1400	462 000	15 200
2	41 200	38 100	37 500	760	488 000	50 300
3	22 000	14 000	18 900	219	254 000	41 000
4	15 400	12 200	90 800	649	259 000	8860

Earthworks represents 60 and 85% of the total emissions (1.42 10^{5} - 3.82 10^{5} tCO2e). This difference could be due to the complex Spanish orography (need of embankments). In Spain, earthworks accumulate the highest percentage of road project costs (between 20 and 40% of total road construction cost in the 4 case studies).

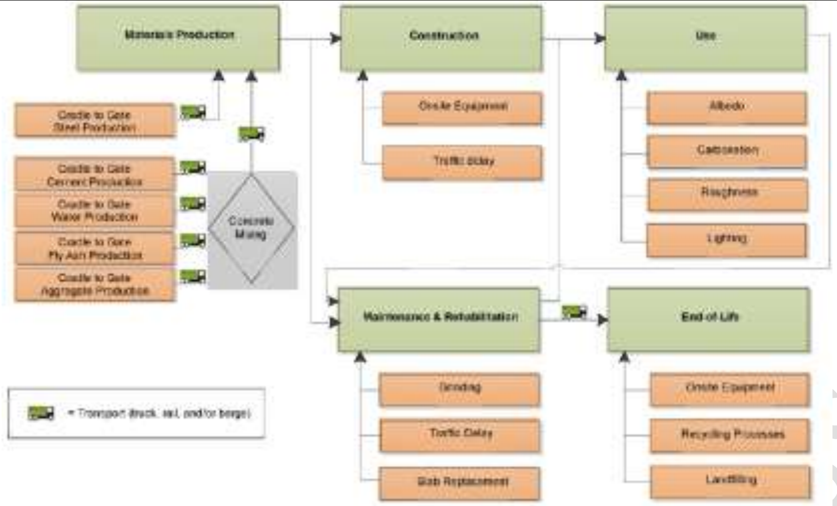
Off-road machinery was responsible of the greater emissions for the majority of the impact categories. Materials production is the second emissions source and this result is coherent with the importance of earthworks in the 4 case studies. Land use and land-use change result significant and crucial contributions.

Results suggest that efforts aimed at controlling and reducing emissions have to focus first on earthworks and on improvements in off-road machinery performance. Secondly, the choice of construction materials as well as the processes of disruption and restoration of environmental systems

A final consideration is that even though vehicular traffic is not within the scope of infrastructure LCA, an integrated management of emissions from transport infrastructures would require carrying out an analysis which takes it into account, evaluating the consequences of different routes, road surfaces, maintenance works (such as improvements to the quality of road surface etc.), and the emissions generated by traffic on a long term scale. However, it is necessary to establish a clear, feasible, stable standard of traffic evaluation

Strengthens and weakness of the whole study, general comments	One of the strengths of the study is the CO2NSTRUCT tool, which contains a database that has a fundamental geographic coherence (85% of the items was determined at national level). Real projects	$S_{ROBUSTN}$ = 3
Subject to independent review?	Peer review	S_{REVIEW} = 3
		21.33

		Scoring
Authors	Loijos A., Santero N. and Ochsendorf J.	
Year	2013	
Title	Life cycle climate impacts of the US concrete pavement network.	
Reference (journal, pagg…)	Resources, Conservation and Recycling 72, 76– 83	
Type of study	According to ISO 14040 (2006)	S_{SCOPE} = 5
Scope	The aim of the study is to develop a general pavement LCA methodology and apply it to the life cycle of concrete pavements in order to quantify current emissions across the U.S. road network. In detail, GHG emissions of new and reconstructed concrete pavements (approximately 12% of US paved roads) are analysed	
Functional unit	Multiple functional units to characterize various classifications of concrete pavement roadways: 1 centerline-km for 12 different traffic loadings in 40 years of operation (which includes 2 rehabilitation activities at year 20 and 30) ranging from 177 to 22,074 AADT for rural roads and from 980 to 78,789 AADT for urban roadways	
System boundaries (stages and process cut-off)	Phases (broken down into multiple components for each life-cycle phase): - Materials production - Construction - Use (excluding normal traffic but including traffic delays due to construction and rehabilitation strategies) - Maintenance (concrete rehabilitation includes 4% slab replacement and complete surface grinding) - Recycling and disposal at end of life is also included.	

		
Assumptions (e.g. allocation)	Vehicle fuel consumption is only allocated to a pavement based on roughness increases over the life cycle, as the majority of fuel consumption is attributable to the vehicle life cycle, and only a marginal amount is caused by the pavement. Thus, the pavement roughness at initial construction is taken to be the baseline roughness, and GHG emissions from fuel consumption are calculated based on the progressive increase from that initial roughness. Fuel consumption due to the structural deflection of the pavement is excluded from this section due to the assumption that deflections did not change over the life cycle. This differential approach ensures that impacts are only allocated to the pavement that are caused by the pavement itself. Lighting requirements remain constant during the analysis period, making the baseline lighting demand and final lighting demand equal, and their associated emissions are assumed to be zero for the baseline scenario, but is included so as to evaluate the effect of pavement albedo on reducing lighting needs Albedo is light in color (α= 0.40) at initial construction and each time it is newly grinded, but is only attributed GWP as it darkens to a minimum albedo of α 0.25 by year 20 at an assumed constant rate Emissions due to normal traffic are not included, but the traffic delays due to construction and rehabilitation activities are attributed to the pavement Also not included in the scope of this analysis are the following elements deemed insignificant (i.e. less than 1% for most roads) to the life cycle: capital goods production (excavation and paving machinery, production plant equipment, oil refinery infrastructure, etc.), production of roadway lighting hardware, road paint production and application, and joint sealant	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	The life cycle inventory (LCI) data for the analysis is obtained from published literature and LCI databases Road data derives from "Highway Statistics 2008" developed by the Federal Highway Administration. Properties of concrete are from ACPA application library (American Concrete Pavement Association, 2011) The fly ash substitution value is based on an estimated national average utilization of fly ash in concrete in 2008 (American Coal Ash Association, 2008; United States Geological Survey, 2008) Data on structures are derived using American Association of State Highway Officials (AASHTO) pavement design methods	S_{DATA} = (3+3+3)/3= 3
Calculation methodology/ programme	Calculations performed according to ISO 14040-44. A sensitivity analysis is performed by using parameterization in GaBi.	
Impact assessment categories/methods	Impact assessment (CML 2011) - GHG emissions The characterization factors for GHGs are obtained from the report by the Intergovernmental Panel on Climate Change 2009 (classification A) While climate change is a preeminent environmental issue, it is important to acknowledge that other impact categories (e.g., human health impact, water consumption, energy consumption) need to be considered	$S_{IMPACTS}$ = 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	Total life-cycle GWP ranges from 440 Mg CO_2e/km on the rural local road to 6,670 Mg CO_2e/km on the urban interstate (more massive structures). The interval reflects the size of the road, traffic volumes (thus fuel consumption) Cement production emissions are the largest contribution for every one of the 12 structures ranging from 43% (for the urban interstate) to 56% (for the rural local road) of the total lifecycle emissions. The second largest contribution is "fuel consumed from roughness" in every case except for rural and the urban local road, where end of life disposal is the second largest contribution. While the majority of life-cycle GHG emissions are due to cradle to gate materials production and pavement construction at the beginning of the analysis period, there are several effects occurring continuously throughout the use phase (albedo, carbonation, and fuel consumption	S_{OUTC} = 5

	due to roughness) and several one-time events after production (rehabilitation, traffic delay, and end of life demolition, transport, recycling and disposal). The initial emissions in the 1st year– from cradle-to-gate materials production and pavement construction – dominate the time series of emissions (55% of the total for urban interstates). The second largest one-time contribution (9%) is from end-of-life demolition, transport, recycling and disposal. This largely comes from transport and landfill emissions. The majority of emissions occur during materials production, transportation, and end of life (excluding entire use phase), constituting between 64% and 80% on all roads. Between 51% (urban interstates) and 63% (rural other principal arterials) of the total emissions occur in year one – from cradle-to gate materials production, and pavement construction. The second largest contribution derives from fuel consumed due to roughness of the road – except for the smaller, urban road. The life-cycle GHG emissions for all new concrete pavements constructed in the U.S. are approximately 3.1 Tg CO_2e per year (48% due to rural network amd 52% due to urban network), or about 0.05% of total national emissions in 2009. Of the model parameters analyzed for sensitivity, the results are most sensitive to traffic volume, varying the results by up to 60%. The results are also particularly sensitive to parameters affecting the cement emissions, such as shoulder width, lane width, and cement emission factor, as well as aggregate transportation distance, and use phase parameters, such as IRI at year 20 and pavement. The results become more sensitive to certain parameters moving from smaller to larger roads (such as regional climate variability of the pavement's international roughness index (IRI) over time), while other parameters are more important on the smaller roads (e.g., outer shoulder width, carbonation rate, pavement albedo). Larger roads are sensitive to traffic-related parameters, since the roughness and traffic delay components comprise a larger proportion of overall emissions. Strategies for reducing the GHG emissions: 1. reducing embodied emissions : by preventing overdesign of the road. Another effective strategy involves mix design optimization, by replacing cement with supplementary cementitious materials such as coal fly ash, blast-furnace slag, and silica fume (Tikalsky et al., 2011). 2. reducing use phase emissions: reducing pavement roughness, which is currently the second largest life-cycle contribution on most road-way classifications. By increasing the pavement albedo 3. reducing emissions at end of life: concrete's ability to directly absorb carbon dioxide through carbonation, once concrete is crushed	
Strengthens and weakness of the whole study, general comments	A sensitivity analysis is performed	$S_{ROBUSTN}$ = 5
Subject to independent review?	Peer review	S_{REVIEW} = 3
		24

		Scoring
Authors	Liljenström C.	
Year	2013	
Title	Life Cycle Assessment in Early Planning of Road Infrastructure. Application of The LICCER-model.	
Reference (journal, pagg…)	Master of Science Thesis at KTH Royal Institute of Technology, Sweden	
Type of study	Evaluation of LICCER model. The project LICCER (Life Cycle Considerations in EIA of Road Infrastructure) aims to develop a life cycle model (the LICCER-model) for assessment of GHG-emissions and energy use in early planning of road infrastructure. Early planning is defined as choice of road corridor and choice of construction type – plain road, tunnel or bridge. The LICCER-model is based on the Norwegian model EFFEKT which is regularly used for early planning in Norway, and covers material production, construction, operation and maintenance and demolition of the road infrastructure. Additionally, also operation of traffic on the road is included. The LICCER-model will enable national road agencies and other stakeholders to compare different road corridor alternatives in the decision-making process (Brattebø et al., 2013).	S_{SCOPE} 3
Scope	This thesis is limited to LCA for roads in early stages of infrastructure planning, i.e. at the stage where road corridor and construction type is chosen. LICCER-model is applied to a case study for choice of road corridors in early planning of road infrastructure. Road 55 is located in the south-east of Sweden, between Norrköping and Uppsala. The part of the road that is analysed in this case study is an approximately 7 km long road section located between Yxtatorpet and Malmköping, three alternatives of design are evaluated	
Functional unit	"road infrastructure enabling annual transport from "A" to "B" over an analysis time horizon of a defined number of years" (Brattebø et al., 2013).	

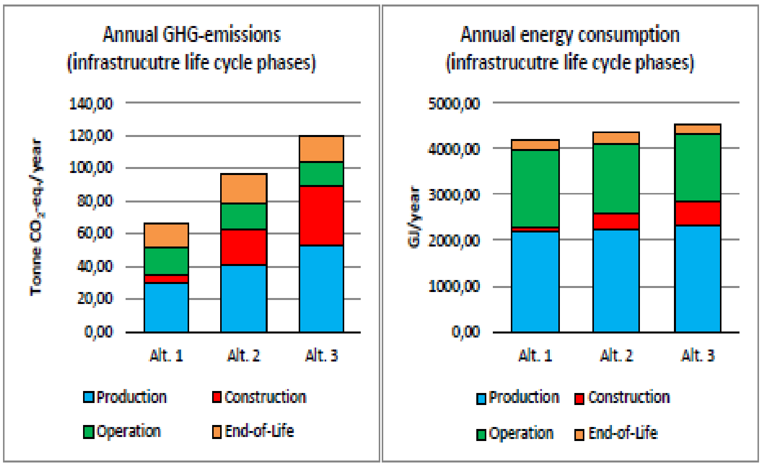
<table>
<tr><td>System boundaries (stages and process cut-off)</td><td>Production includes production of bitumen and aggregates, as well as other materials needed for road construction. Table B-1 in Appendix B provides an overview of the different materials that are included in the LICCER-model for the different road elements. The inventory data for the production phase includes excavation of raw material, transportation of materials and processing of these materials to construction components. This constitutes background data in the model and is gathered from databases and the LCA-literature.
Construction is in the LICCER-model taken into account by transportation of materials to the construction site, in addition to earthworks and construction of tunnels. Different types of rock and soil has been categorised depending on the work needed to excavate the materials: (i) simple excavated soil, (ii) ripped soil and (iii) blasted rock. The environmental impacts are calculated based on the fuel consumption required for excavation of a specified volume of a specific type of rock or soil.
Operation of the road infrastructure includes maintenance of the road surface by reasphaltation (including production of materials and transportation of these materials to the construction site), and operational activities such as road lighting and ventilation of tunnels.
The end-of-life stage includes material removal and deconstruction of the road (including bridges and guardrails), transportation of materials to landfill and depots, and earthworks necessary to restore the land area back to natural conditions. It is assumed that lining materials inside tunnels are left behind and that there will be no GHG-emissions from the deposit or landfill. Recycling and reuse of materials in the end-of-life stage is left outside the system boundary of the analysis.
Traffic on the road is accounted for by the average AADT on the road over the analysis period, share of different types of fuels (diesel, gasoline, biofuel, electricity) and share of different types of vehicles (light vehicles, heavy vehicles with trailer, heavy vehicles without trailer).
LICCER-model is constructed for use in Norway, Sweden, Denmark and the Netherlands</td><td rowspan="2"></td></tr>
<tr><td>Assumptions (e.g. allocation)</td><td></td></tr>
<tr><td>Data sources and quality
1. Raw materials production phase
2. Production phase
3. Road construction phase
4. Use phase
5. Maintenance and operation phase
6. End of Life phase</td><td></td><td rowspan="2">SDATA
1</td></tr>
<tr><td>Calculation methodology/ programme</td><td>LICCER</td></tr>
<tr><td>Impact assessment categories/methods</td><td>GHG emissions and energy consumption as the average values per year for the analysis time horizon.</td><td>SIMPACTS
3</td></tr>
<tr><td>Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)</td><td>


Figure 10. Annual GHG-emissions and energy consumption from infrastructure life cycle phases for the three road corridors.</td><td>SOUTC
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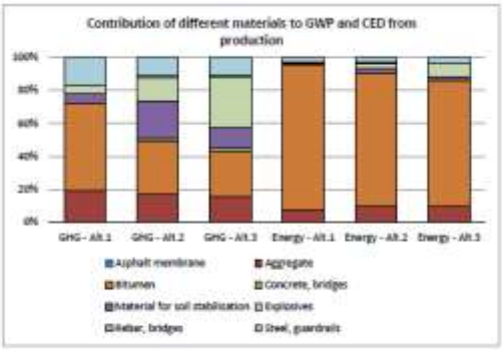


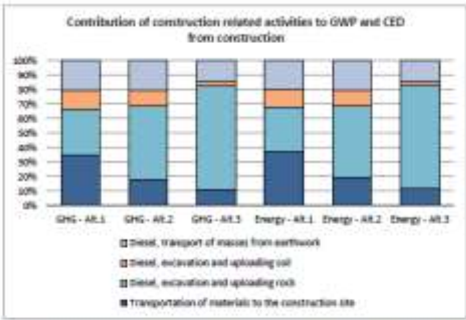
Figure 13. Contribution of different materials to GHG-emissions and energy consumption from the production stage.


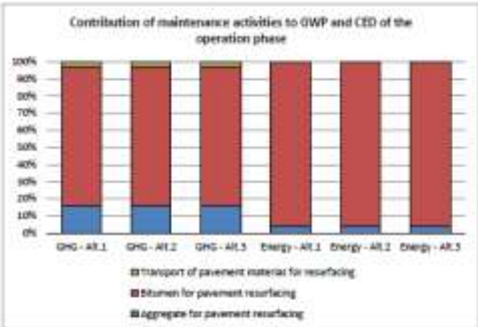
Figure 14. Contribution of different construction related activities to GHG-emissions and energy consumption from the construction phase.


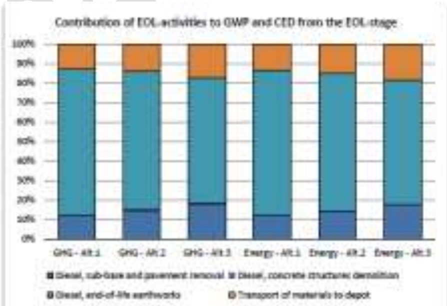
Figure 15. Contribution of operation activities to GHG-emissions and energy consumption from the operation phase.


Figure 16. Contribution of end-of-life activities to GHG-emissions and energy consumption from the end-of-life phase.
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<tr>
<td>Strengthens and weakness of the whole study, general comments</td>
<td>Sensitivity analysis
Geographical boundaries</td>
<td>S_{ROBUSTN} 5</td>
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<td>Subject to independent review?</td>
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<td>S_{REVIEW} 1</td>
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<td>17</td>
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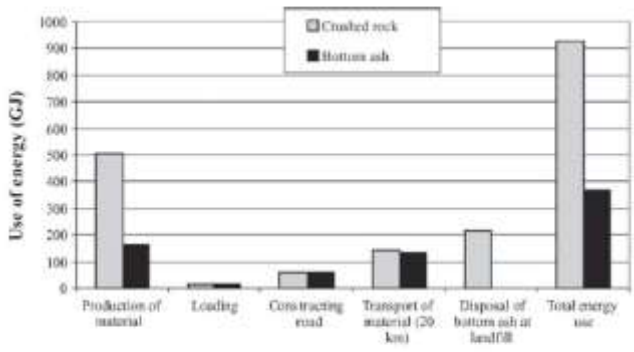
Supply chain

		Scoring
Authors	Birgisdóttir H.	
Year	2005	
Title	Life cycle assessment model for road construction and use of residues from waste incineration	
Reference	Ph.D. Thesis. DTU University	
Type of study		S_{SCOPE} = 3
Scope	Two cases are investigated: I) Comparing disposal of 4,400 tons bottom ash in landfill compared with the use of recycled bottom ash for sub-base layer in secondary road II) Construction of secondary road with conventional material compared with bottom ash as sub-base material.	
Functional unit	I) 4,400 tonnes of bottom ash disposed at landfill during 100 years II) 4,400 tonnes of bottom avoiding the use of natural gravel material in the sub-base of a road construction operated and maintained for 100 years	
System boundaries (stages and process cut-off)	Phases: I) Disposal phase (landfill or road construction) II) Design phase (including production of materials) • Construction phase • Operation and maintenance phase • No end-of-life/demolition Bottom ash substitute natural gravel in bottom layer and the impact from mining and transportation of natural gravel are there for avoided. Bottom ash area occupation: 300 m² (thickness 8 m) in landfill and 7000 m² in road (thickness 0.37 m). The transportation distance of bottom ash is 50 km to road construction site and 20 km to landfill.Danish secondary road: assumed to consist of two lanes (2x3.5m), two reserves between lanes and bicycle paths (2x1.5m), two bicycle paths (2x1.5m) and two shoulders (2x2.1m). The total width of the road was 17.2m. The total thickness of the road construction was 0.7 m.	
Assumptions	The infiltration from road with bottom ash is 10 % and the distribution of heavy metals is 85% soil and 15 % marine water throughout the entire life time of the road construction. Inputs and outputs in the operation and maintenance were assumed to remain constant over the period. The operation and maintenance technologies are fixed during the life time of the road construction. The result is very sensitive to assumptions about the water infiltration.	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Data for the ROAD-RES model are collected from several sources. The data on production of materials have, as far as possible, been collected from material producers. Data on machinery and processes in road construction have also as far as possible been collected from contractors in the road sector in Denmark. Data material on many processes in road construction was available in Stripple (2001). The leaching data used in the model are all based on laboratory leaching tests. Data concerning the content of selected constituents in bottom ash, fly ash, semi-dry APC residues and gravel pit materials has mainly been obtained from the Danish power plant I/S Vestforbrænding from samples taken during 1993-2001.	S_{DATA} = (3+3+3)/3=3
Calculation methodology/ programme	ROAD-RES was develop during the study including methods for predicting leaching from materials as well as the distribution of leached constituents into the five environmental compartments; air, soil, groundwater, fresh surface water and marine surface water. The model ROAD-RES also includes two new characterization methods: 1. For contamination of groundwater due to leaching of salts (Potentially spoiled groundwater resource) 2. Human toxicity via groundwater due to emissions of heavy metals	
Impact assessment categories/methods	Furthermore, a new impact category was developed: Stored ecotoxicity in water and soil that accounts for the presence of heavy metals and very persistant organic compounds that may leach in the long term. EDIP97 is chosen as the default impact assessment method. The model allows for the incorporation of the impact assessment methods Eco-indicator 95, Eco-indicator 99 and CML2001. Impact categories: - Global Warming impact (GW) (classification A) - PhotoChemical Ozone Formation (POF) (classification B) - Nutrient enrichment (NE) (classification E) - Acidification (AF) (classification B) - Human toxicity air (HTa) - Human toxicity water (HTw) - Human toxicity soil (HTs)	$S_{IMPACTS}$ = 3

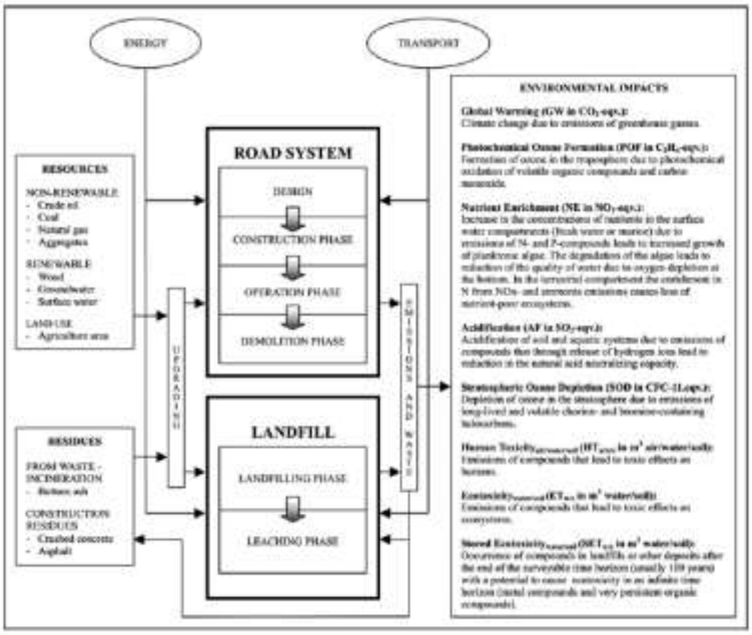
	- Ecotoxicity water (ETw) - Ecotoxicity soil (ETs) After 100 years - Stored ecotoxicity water (SETw) - Stored ecotoxicity soil (SETs)	
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	I) The main impact category from bottom ash is ecotoxicity water, mainly due to leaching of copper (90%) from bottom ash. The road scenario results in 40 PE for ecotoxicity in water and 30 PE in the landfill scenario. A sensitivity analysis (99 % of heavy metal for soil, which was considered more likely) showed an ecotoxicity in water of 5 PE. Human Toxicity soil was the second greatest impact for the road scenario (around 8 PE), mainly due to leaching of arsenic from bottom ash. Other impact categories were mostly related to combustion of fossil fuels. Almost the same picture for stored ecotoxicity in water in both scenarios, with the bottom ash still containing 99% of its ecotoxicity potential after 100 years. It can be concluded that the by far largest content of heavy metals in the ash was still remaining in the ash and few centimeters below after 100 years. II) The difference between a road with and a road without bottom ash as base-layer was found insignificant in all environmental impact categories given that the avoided impact from landfills is included. The biggest impact category was global warming mainly from combustion of fossil fuels (150 PE). After 100 years is the stored ecotoxicity water/soil are approximately 400-450 PE. The most important resource consumption was the potentially spoiled groundwater resource due to leaching of salts into the groundwater department. Approx. 10% of this impact was caused by the application of bottom ash whereas the remaining 90% of the potential impact was caused by road salting due to winter maintenance. Consumption of natural aggregate was also important. The construction and production of materials caused approx. half of the emissions while operation and maintenance of the road caused the other half of the total emissions.	S_{OUTC} = 5
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?	Ph.D. Thesis. DTU University	S_{REVIEW} = 1
		17

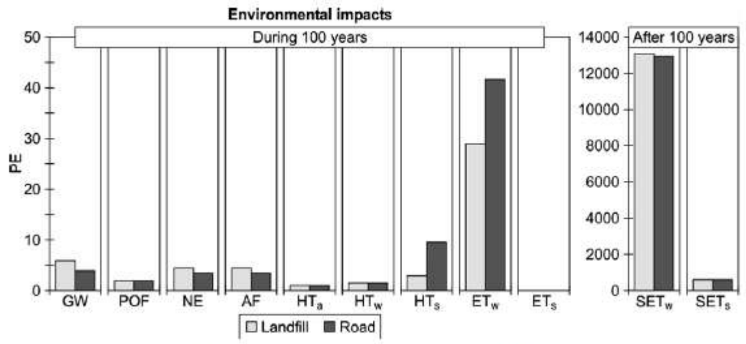
		Scoring
Authors	Olsson S., Kärrman E. and Gustafsson J.P.	
Year	2006	
Title	Environmental systems analysis of the use of bottom ash from incineration of municipal waste for road construction	
Reference	Resources, Conservation and Recycling 48,pp. 26–40	
Type of study	ISO, 1997	S_{SCOPE} = 3
Scope	To describe what differences in resource use and emissions can be expected if crushed rock were substituted by MSWI bottom ash within the sub-base of a road in the Stockholm region in Sweden. Emphasis is paid on risks of contaminant leaching and little attention is paid to resource use and emissions that do not originate from the road materials	
Functional unit	- 1 km of road - Alternative 1) bitumen bound surface (thickness 130 mm) – crushed rock in the base course (80 mm) - crushed rock used as an unbound sub-base materials (465 mm). MSWI bottom ash is landfilled - Alternative 2) bitumen bound surface (thickness 130 mm) – crushed rock in the base course (150 mm) - MSWI bottom ash in substitution of crushed rock in the same sub-base layer	
System boundaries	Phases (significant for the base course and the sub-base layers) - Production of raw materials and transportation - Construction - Alternative disposal of 5200 t of MSWI bottom ash The parts of the system that were similar between the two cases were excluded A demolition stage has not been included	
Assumptions		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and**	No data older than from 1990 were used. Most data were average values for Sweden. Transport distance for both crushed rock and MSWI bottom ash is 20 km. Data were obtained from the literature and by interviews with people working in the sector. Data on road construction (Stripple (2001) and on interviews) Data on disposal of MSWI bottom ash (Tillman et al., 1991; Mingarini, 1996; Sundqvist et al., 1997; Bjorklund, 1998). National data for the use of energy and the use of ballast material in the Swedish construction sector (Andersson et al., 2003; SGU, 2003).	S_{DATA} = (1+5+3)= 3

operation phase **6. End of Life phase**	Data on use of fuel, pre-combustion values for fuel production (Stripple (2001). Official statistics for emissions to air (Feldhusen et al., 2004; Hammarskjold et al., 2004). National values are based on official statistics 2000 for emissions from municipal waste water treatment plants, pulp and paper industry and some other coastal-based industry in Sweden for COD and N-tot (Branvall and Widell, 2002). Leaching of metals was estimated from leaching tests results (Tossavainen and Hakansson, 1999; RVF, 2002) For the metals the normalization is based on emissions per person in the Stockholm region (Bergback et al., 2001).	
Calculation methodology/ programme	Environmental systems analysis (ESA) on the use of MSWI bottom ash for road construction as material in the sub-base layer, that could be helpful in a SEA approach. ESA is a method to describe environmental impact of a system from a holistic point of view, including all subsystems and their interrelations	
Impact assessment categories/methods	Impact categories described by SETAC-Europe (1999) - use of resources (natural aggregates and energy) - emissions to air (SO2, NOx, CO, CO2, HC, CH4, VOC, N2O and particles) - emissions to water (COD, N-tot, Oil, Phenol, As, Cd, Cr, Cu, Ni, Pb and Zn). Use of machinery and human resources, and occupation of land area were not considered. Other excluded environmental aspects were the energy and material used for final covering of the landfill, dust, noise, and leaching of some substances (i.e. Mo, SO42− and Cl−) Normalization is performed according to the national flow of each kind per person in Sweden	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The use of energy and natural aggregates, the release of metals and As, and the emissions of NOx, CO_2 and SO2 were of greater significance than the other flows *Sensitivity analysis on transport:* MSWI bottom ash had to be transported more than 140 km, alternative 2 would use more energy than alternative 1.  *Fig. Use of energy by each stage in the system* The results showed that the use of MSWI bottom ash instead of crushed rock in the sub-base layer of a road would lead to less energy use and less energy derived emissions. On the other hand, the leaching of some metals (Cd, Cr, Cu, Ni, Pb and Zn) can be expected to be larger from the road if MSWI bottom ash is used. Parameters that may change these results are the transport distance for the material and the conditions affecting contaminant leaching. It should be emphasized that the results depend on several assumptions and estimates used in the case; in particular the leaching estimates are uncertain. Therefore, further research is needed on hydrological conditions in roads and leaching mechanisms of the material in the road under field conditions.	S_{OUTC} = 3
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 3
Subject to independent review?		S_{REVIEW} = 3
		16

In Sweden 400 kt/y of MSWI bottom ash

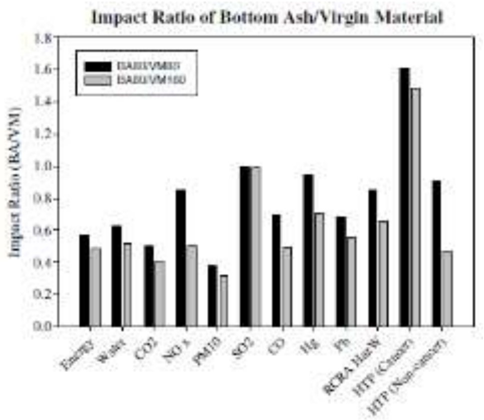
		Scoring
Authors	Birgisdóttir H., Bhander G., Hauschild M.Z., Christensen T.H.	
Year	2007	
Title	Life cycle assessment of disposal of residues from municipal solid waste incineration: Recycling of bottom ash in road construction or landfilling in Denmark evaluated in the ROAD-RES model	
Reference	Waste Management 27, pp. S75-S84	
Type of study	ISO 14040-14043 (ISO, 1997)	S_{SCOPE} = 3
Scope	Analysis of two disposal methods for MSWI bottom ash by means of the model ROAD-RES for road construction and disposal of residues.	

	The LCA included resource and energy consumption, and emissions associated with upgrading of bottom ash, transport, landfilling processes, incorporation of bottom ash in road, substitution of natural gravel as road construction material and leaching of heavy metals and salts from bottom ash in road as well as in landfill	
Functional unit	- 4400 tonnes of bottom ash disposed at landfill during 100 years - 4400 tons bottom ash, equivalent to the amount of bottom ash needed for sub-base material beneath the lanes in 1 km traditional Danish secondary road (life time 100 y) Danish secondary road: assumed to consist of two lanes (2x3.5m), two reserves between lanes and bicycle paths (2x1.5m), two bicycle paths (2x1.5m) and two shoulders (2x2.1m). The total width of the road was 17.2m. The total thickness of the road construction was 0.7 m. Evaluated scenarios: 1. landfilling of bottom ash in a coastal landfill in Denmark 2. recycling of bottom ash as sub-base layer in an asphalted secondary road.	
System boundaries	ROAD-RES Phases: - Construction including earth works (including also road lighting, signs, safety barriers, etc.). - Operation and maintenance (1. Regular maintenance including also cleaning and maintenance of vegetation 2. Pavement maintenance 3. Winter service, including also road salting and snowing clearance 4. Leaching aspects) - demolition  In the study the EoL phase is excluded. Bottom ash substitute natural gravel in bottom layer and the impact from mining and transportation of natural gravel are there for avoided. Bottom ash area occupation: 300 m² (thickness 8 m)in landfill and 7000 m² in road (thickness 0.37 m) The transportation distance of bottom ash is 70km from the incineration plant, 50 km to road construction site and 20 km to landfill. The average infiltration of water through the asphalt layers was 10% of the yearly precipitation of 700 mm/year and the distribution of heavy metals is 85% soil and 15 % marine water throughout the entire life time of the road construction. The result is very sensitive to assumptions about the water infiltration. The leaching of heavy metals during 100 years is less than 1% of the total amount in the bottom ash for all heavy metals Leaching from the landfill and the road was calculated for a period of 100 yr. After 100 yr, the heavy metals remaining in the landfill or in the road construction contributed to Stored Ecotoxicities Inputs and outputs in the operation and maintenance were assumed to remain constant over the period. The operation and maintenance technologies are fixed during the life time of the road construction.	
Assumptions (e.g. allocation)	The disposal part of the model quantifies energy consumptions, leaching from the residues and avoided consumption of resources and environmental impacts through recycling of residues. In the disposal part of the model, the environmental impacts included are related only to the residues. This means that for utilization of bottom ash in road, only emissions from the bottom ash are included and all emissions from the other materials in the road construction are excluded. The disposal part of the model enables the user to perform comparisons of	

	environmental impacts and resource consumption when residue is landfilled or recycled in roads. When a residue is utilized in road construction, the user has the option of subtracting the impacts that are avoided from the substituted natural material (both production of materials, transport and leaching).	
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Data for the ROAD-RES model are collected from several sources. Data on production of materials collected from material producers. Data on machinery and processes in road construction collected from contractors in the road sector in Denmark and EDIP database Data for energy consumption: average data for Danish electricity for the year 2001 (Energi E2, 2004) Data material on many processes in road construction from Stripple (2001). Leaching data based on laboratory leaching tests. Data concerning the content of selected constituents in bottom ash, fly ash, semi-dry APC residues and gravel pit materials obtained from a Danish power plant (sampling campaign in 1993-2001)	S_{DATA} = (3+3+3) = 3
Calculation methodology/ programme	ROAD-RES model includes methods for predicting leaching from materials as well as the distribution of leached constituents into air, soil, groundwater, fresh surface water and marine surface water. The model ROAD-RES also includes two new characterization methods: - For contamination of groundwater due to leaching of salts (Potentially spoiled groundwater resource) - Human toxicity via groundwater due to emissions of heavy metals Furthermore, a new impact category was developed: Stored ecotoxicity in water and soil that accounts for the presence of heavy metals and very persistant organic compounds that may leach in the long term.	
Impact assessment categories/methods	EDIP97 (Wenzel et al., 1997, Hauschild and Wenzel, 1998) as the default impact assessment method. Incorporation of the impact assessment methods Eco-indicator 95(Goedkopp, 1995), Eco-indicator 99 (Goedkoop and Spriensma, 2000) and CML2001 (Guinée, 2001). Impact categories: - Global Warming impact (GW) (classification A) - PhotoChemical Ozone Formation (POF) (classification B) - Nutrient enrichment (NE) (classification E) - Acidification (AF) (classification B) - Human toxicity air (HTa) - Human toxicity water (HTw) - Human toxicity soil (HTs) - Ecotoxicity water (ETw) - Ecotoxicity soil (ETs) After 100 years - Stored ecotoxicity water (SETw) - Stored ecotoxicity soil (SETs)	$S_{IMPACTS}$ = 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	$Ecotoxicity_{water}$ is the largest environmental impact during the 100-yr period, contributing with 30 PE in the landfill scenario and 40 PE in the road scenario. The difference between other environmental impacts is marginal. Human Toxicity soil was the second greatest impact for the road scenario (around 8 PE), mainly due to leaching of arsenic from bottom ash. Stored $Ecotoxicity_{water}$ is the most dominating environmental impact when impacts are assessed for more than 100 yr, with approximately 13,000 PE for both alternatives. The distribution of heavy metals in the environmental compartments (fresh surface water and soil) after leaching from the material was based on calculations on sorption of heavy metals in soil. The calculations indicated that the heavy metals migrated only a few centimeters in the soil during 100 years and therefore it is unlikely that to any large extent they would end up in the water compartments. The impacts in terms of $Ecotoxicity_{soil}$, are however not noticeable. This is due to the fact that the characterization factors for ETs normally are five orders of magnitude less than the characterization factors for ETw reflecting the limited bioavailability of the metals in the soil Copper is the constituent that contributes with the greatest environmental impacts, both during the first 100 yr and after.  *Fig. Normalised environmental impacts (in PE representing the annual impact from an average person) of the landfill scenario and the road scenario according to the EDIP97 method*	S_{OUTC} = 5

	The largest resource impacts appear in the road scenario. These are a potentially spoiled groundwater resource of 1400 PE and potential savings of natural gravel equivalent to 400 PE. Depending on the local condition of the landfill, the landfill scenario can potentially have a considerable consumption of clay of 3700 PE.	
Strengthens and weakness of the whole study, general comments	Sensitivity analysis Several scenarios (named B–F) covering a range of varying parameters were analyzed in order to assess which parameters in the road and the landfill scenarios were most influencing the results. The sensitivity analysis showed that $Ecotoxicity_{water}$ was most sensitive to the tested assumptions, and the water movement in road and the fate of constituents leached out from the residue were important factors for the result	$S_{ROBUSTN}$ = 3
Subject to independent review?	Peer review	S_{REVIEW} = 3
		21

		Scoring
Authors	Carpenter A.C., Gardner K.H., Fopiano J., Benson C.H., Edil T.B.	
Year	2007	
Title	Life cycle based risk assessment of recycled materials in roadway construction.	
Reference (journal, pagg…)	Waste Management 27, pp. 1458-1464	
Type of study		S_{SCOPE} = 3
Scope	To characterize comparative environmental impacts from the use of virgin aggregate and recycled materials (coal fly ash, coal bottom ash, foundry slag and foundry sand) in roadway construction. The use of coal ash in unconsolidated fill is still a point of concern due to potential impacts from leaching of contaminants out of the recycled materials into the groundwater	
Functional unit	305 m of road (width 10.4 m, shoulder 1.5 m, stabilized sub – grade 13.4 m, depth of the vadose zone 6 m)	
System boundaries (stages and process cut-off)	Phases: - materials production, - the road environment, - the road environment plus transport and pre-treatment of materials - industrial system level including mining and production of materials, material processing, transportation, manufacturing of necessary equipment, administrative processing, product assembly, distribution, sale, use, repair, and ultimate disposal and looks at overall environmental impacts.	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**		S_{DATA} = (3+1+3) = 2.33
Calculation methodology/ programme	Two modeling tools - Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) considers materials, designs parameters, equipment and maintenance and cost inputs - HYDRUS2D simulating the impact of use of recycled materials	
Impact assessment categories/methods	- Energy - Water - CO2 - NOx - PM10 - SO2 - CO - Hg - Pb - RCRA - HTPcancer - HTP non cancer	$S_{IMPACTS}$ = 1
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts -	The combination of a LCIA (at macro-scale regional/national) assessment of environmental costs and benefits related to recycled materials use, and a micro-scale (site-specific) risk assessment can provide a unique perspective that may be useful in considering trade-offs associated with recycled material use.	S_{OUTC} = 3

process/material; improvement options)	In comparing the PaLATE results for virgin material (crushed rock) with bottom ash at equivalent source distances, in almost all impact categories, bottom ash has significantly less impact than crushed rock. The exceptions are SO_2 and HTP Cancer, where crushed rock has significantly less impact than bottom ash  Ratio of impacts from use of bottom ash (BA) in roadway construction compared to virgin materials (VM): BA source at 80 km, VM source at 80 and 160 km. Ratios less than 1.0 indicate that impacts due to virgin material are greater than impacts due to bottom ash. The black bar indicates the ratio of impacts for materials sources at equal distances. The grey bar indicates the ratio of impacts for materials with the source for virgin materials being twice that of the bottom ash. Hydrus2D simulations were run to predict contaminant (Cd, Cr, Se and Ag for this study) transport through the subsurface material (vadose zone) to the groundwater. The simulations indicate that Se and Cr leached from the bottom ash used in the sub-base of the road will not reach the groundwater located 5 m below the surface even after 200 years. The level of contaminants predicted to reach the groundwater after 200 years was significantly less than groundwater maximum contaminant levels (MCL) set by the US Environmental Protection Agency for drinking water.	
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?		S_{REVIEW} = 3
		13.33

		Scoring
Authors	Carpenter A.C., Gardner K.H.	
Year	2009	
Title	Use of Industrial By-Products in Urban Roadway Infrastructure Argument for Increased Industrial Ecology.	
Reference (journal, pagg…)	Journal of Industrial Ecology, 13 n. 6, pp. 965-977	
Type of study	Tonne-kilometers were also calculated for each case, and the transportation cost was calculated based on 45.6 cents/tonne-km (Eno 2002).	S_{SCOPE} = 3
Scope	Utilization of industrial by-products (IBPs) (coal ash, foundry sand, and foundry slag) as aggregate for roadway sub-base construction for the Pittsburgh, Pennsylvania, urban region. The scenarios compare the use of virgin aggregate with the use of a combination of both virgin and IBP aggregate, where the aggregate material is selected based on proximity to the construction site and allows for minimization of transportation impacts	
Functional unit		
System boundaries (stages and process cut-off)	Phases: - Materials production - Construction Use and maintenance are excluded	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Database from the PaLATE program	S_{DATA} = (3+1+3) = 2.33
Calculation methodology/ programme	Using GIS data for PENNDOT roadway systems (PENNDOT 2008) The Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) EIO	
Impact assessment	Energy	$S_{IMPACTS}$

categories/methods	GWP CO SO_2 NOx PM10 Hg Pb, Hazardous Waste human toxicity potential (HTP) cancer HTP noncancer (Horvath 2004). Person equivalents (PE) were also determined for all impacts (WRI 2007; UNSD 2004; USEPA 1999, 2005) except the HTPs (no information was available to make valid PE conversions for HTPs).	= 3
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	The results indicate that the use of virgin aggregates in the base course for roadway construction generates greater impacts in all the categories calculated except HTP cancer, which is about 10% greater for the combined IBP and virgin material usage than for virgin material alone. The HTP cancer impacts for the IBPs are based on the leaching potential of the materials. The HTP calculations are highly conservative and do not account for sorption of the contaminants For the impact categories (energy, water, GWP,PM10, Pb, andHTP cancer and noncancer), the majority of the impacts are due to materials processing. NOx and Hg impacts are mostly due to transportation. Impacts are greater in all categories for the scenario with virgin material use alone, approximately doubling the PE impacts for the combined IBP and virgin aggregate usage scenario. The energy consumption, NOx, PM10, and Pb emissions and RCRA Hazardous Waste generation PE impacts range from 500 PEs (energy) to 7,700 PEs (RCRA Hazardous waste generation). The impacts from virgin aggregate usage alone is approximately double that of the combined IBP and virgin aggregate usage	S_{OUTC} = 5

Table 2 Regional impact values per process (material production, material transportation, and process [equipment]), and totals for the use of virgin materials and industrial by-products in roadway sub-base construction for the greater Pittsburgh urban area

		Virgin materials				Industrial by-products & virgin materials			
Impact	Unit	Mat prod	Mat trans	Proc (equip)	Total	Mat prod	Mat trans	Proc (equip)	Total
Energy	TJ	274.8	73.1	7.9	355.8	131.4	38.3	8.7	178.4
Water	Mg	38.3	12.4	0.8	51.5	18.3	6.5	0.8	25.7
GWP	Gg	19.5	5.5	0.6	25.5	9.3	2.9	0.7	12.8
NO_x	Mg	39.2	291.2	12.8	343.3	18.8	152.7	14.1	185.5
PM_{10}	Mg	278.9	56.8	2.2	337.9	133.3	29.8	1.6	164.7
SO_2	Mg	19.1	17.5	0.8	37.4	9.1	9.2	0.9	19.2
CO	Mg	25.6	24.3	2.8	52.7	12.3	12.7	3.0	28.0
Hg	g	0.7	52.8	5.7	59.3	0.3	27.7	6.3	34.3
Pb	kg	5.6	2.5	0.3	8.3	2.7	1.3	0.3	4.3
RCRA HW	Mg	319.4	526.9	56.9	903.2	152.7	276.2	62.5	491.5
HTP cancer	million	33.2	1.6	0.0	34.8	38.0	0.8	0.0	38.8
HTP noncancer	billion	467.1	1.9	0.0	469.0	272.5	1.0	0.0	273.5

Notes: Mat prod = material production; Mat trans = material transportation; Proc (equip) = processing (equipment); GWP = global warming potential; RCRA HW = Resource Conservation and Recovery Act Hazardous Waste; HTP = human toxicity potential; TJ = terajoule; Mg = megagram (tonne); Gg = gigagram; g = gram; kg = kilogram.

The transportation component includes a simple cost analysis based on tonne-km. The virgin aggregate scenario requires the transportation of almost 36 million tonne-km more than the combined IBP and virgin aggregate scenario. It costs almost $9 million over the transportation cost for the combined IBP and virgin aggregate use.

Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?		S_{REVIEW} = 3
		17.33

		Scoring
Authors	Korre A. and Durucan S.	
Year	2009	
Title	Life Cycle Assessment of Aggregates.	
Reference (journal, pagg…)	WRAP Report (EVA025) at http://www2.wrap.org.uk/downloads/EVA025-MIRO_Life_Cycle_Assessment_of_Aggregates_final_report.414207d5.8879.pdf	
Type of study	According to ISO 14040- 14044	S_{SCOPE} = 3
Scope	To develop a Life Cycle Inventory (LCI) and Assessment (LCA) Model for the aggregates industries. The work includes the extraction and processing of primary resources through to the point of their dispatch as aggregates (including overburden stripping, drilling and blasting, and restoration), and comparing with the processing of equivalent recycled aggregates for three grades (aggregates for unbound applications; aggregates for concrete; aggregates for asphalt)	

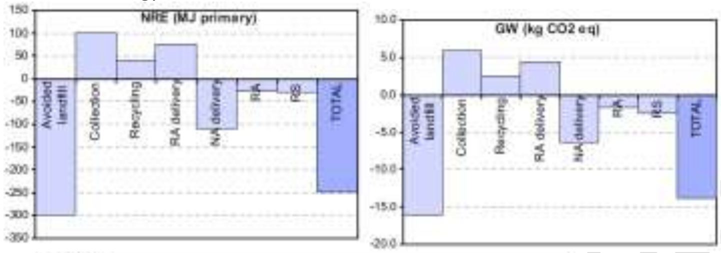
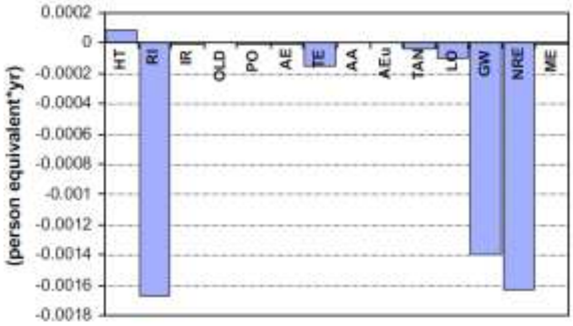
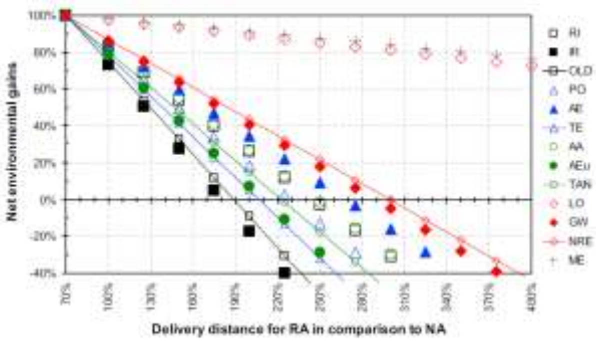
<table>
<tr><td></td><td>from: igneous rocks; sedimentary rocks; sand and gravel deposits (land and marine); recycled unbound inert waste; recycled concrete; and recycled asphalt in particular to ascertain and quantify all the environmental impacts of each phase in the product life cycle</td><td></td></tr>
<tr><td>Functional unit</td><td>Declared unit (ISO 21930:2007) a unit mass of aggregate produced (one tonne of material).</td><td></td></tr>
<tr><td>System boundaries (stages and process cut-off)</td><td>Phases:
- Raw materials extraction
- Materials processing, including waste material processing
- EoL: waste management
The geographical boundary for the study is the UK</td><td></td></tr>
<tr><td>Assumptions (e.g. allocation)</td><td>1% cut-off
The allocation procedure for the environmental loads is based on physical/chemical causation per unit mass of aggregate produced</td><td></td></tr>
<tr><td>Data sources and quality
1. Raw materials production phase
2. Production phase
3. Road construction phase
4. Use phase
5. Maintenance and operation phase
6. End of Life phase</td><td>LCI
The main sources of emissions modelled in the tools are generated from the combustion of fuels used by production equipment, transport vehicles and on site electricity generators. The formulae used to estimate these emissions are taken from the National Atmospheric Emissions Inventory (NAEI, 2003; NAEI, 2000a). In addition, the marine sand and gravel tool includes equations to estimate emissions from shipping (NAEI, 2000b) while the product distribution tool also includes emissions due to rail freight (NAEI, 2000c).
In order to estimate the upstream emissions from electricity and fuel use (diesel and fuel oil), impact category indicator results were generated using the GaBi software. These impacts include the diesel production at refinery (EU-15 Diesel at refinery, ELCD/PE-GaBi) with transportation by truck for 100 km distance; the EU light fuel oil production at refinery (EU-15 Fuel oil light at refinery ELCD/PE-GaBi); and the UK power (GB: Power grid mix ELCD/PE-GaBi). Fuel oil produced at UK refineries is directly loaded to dredgers and ships for marine aggregates extraction and shipping, so no additional transport is considered</td><td>S_{DATA} + (3+5+3)/3=4.33</td></tr>
<tr><td>Calculation methodology/ programme</td><td>1. The Crushed Rock Tool
2. The Land-won Sand and Gravel Tool
3. The Marine Aggregates Tool
4. The Recycled Aggregates Tool
5. The Product Distribution Tool</td><td></td></tr>
<tr><td>Impact assessment categories/methods</td><td>LCIA according to CML2001 baseline categories (Guinée, 2001).
Global Warming (classification A)
Eutrophication (classification B)
Acidification (classification B)
Photo-oxidant formation
Human toxicity
Freshwater Aquatic Ecotoxicity
Marine Aquatic Ecotoxicity
Terrestrial Ecotoxicity
Ozone layer depletion</td><td>$S_{IMPACTS}$ = 5</td></tr>
<tr><td>Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)</td><td><u>Crushed rock aggregates</u>: The case studies used to develop and implement the inventory forms covered soft and hard rock crushed aggregates production sites (limestone and granite quarries respectively) and operations of varied annual production to represent the full range of operations in the UK.
Range of impacts:
<table>
<tr><th>Impact Category
Units</th><th>Product category A
Subbase, capping layers, crusher runs, agricultural lime, scalping, 80-40 mm, 150 mm, 125 mm, 40 mm, dust 6mm, dust 3mm</th><th>Product category B
28 mm, 20 mm, 14 mm, 10 mm</th></tr>
<tr><td>Global Warming
kg CO_2 eq</td><td>0.51-1.35</td><td>2.43-4.14</td></tr>
<tr><td>Eutrophication
kg PO_4 eq</td><td>3.05×10^{-4}-5.65×10^{-4}</td><td>8.24×10^{-4}-1.31×10^{-3}</td></tr>
<tr><td>Acidification
kg SO_2 eq</td><td>3.28×10^{-3}-6.41×10^{-3}</td><td>1.39×10^{-2}-2.38×10^{-2}</td></tr>
<tr><td>Photo-oxidant formation
kg ethylene eq</td><td>2.89×10^{-4}-6.27×10^{-4}</td><td>8.95×10^{-4}-1.51×10^{-3}</td></tr>
<tr><td>Human toxicity
kg 1,4-DB eq</td><td>0.22-0.35</td><td>0.44-0.63</td></tr>
<tr><td>Freshwater Aquatic Ecotoxicity
kg 1,4-DB eq.</td><td>4.35×10^{-3}-7.26×10^{-3}</td><td>7.23×10^{-3}-1.14×10^{-2}</td></tr>
<tr><td>Marine Aquatic Ecotoxicity
kg 1,4-DB eq.</td><td>74.79-141.46</td><td>1.81×10^{2}-3.20×10^{2}</td></tr>
<tr><td>Terrestrial Ecotoxicity
kg 1,4-DB eq.</td><td>1.94×10^{-3}-3.26×10^{-3}</td><td>3.31×10^{-3}-5.26×10^{-3}</td></tr>
<tr><td>Ozone layer depletion
kg R11 eq.</td><td>4.32×10^{-8}-1.68×10^{-7}</td><td>3.24×10^{-7}-5.76×10^{-7}</td></tr>
</table>
<u>Recycled aggregates</u>: Recycled aggregates system example: Percentage contribution of impacts due to transport and on site processes for the production of one tonne of different recycled aggregate products and the range of actual impact values in kg equivalent</td><td>S_{OUTC} + 3</td></tr>
</table>

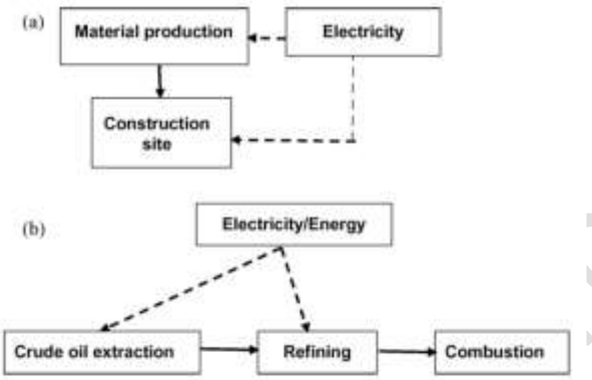
Impact Category Units		Unbound materials	Other bound materials	Washed & graded aggregate	Impact range
Global Warming	P[1] (%)	76.3	81.6	97.7	0.5581 –
kg CO_2 eq	T[2] (%)	23.7	18.4	2.3	5.7384
Eutrophication	P (%)	3.9	4.7	28.2	0.0042 –
kg PO_4 eq	T (%)	96.1	95.3	71.8	0.0056
Acidification	P (%)	3.9	4.2	44.5	0.0389 –
kg SO_2 eq	T (%)	96.1	95.8	55.5	0.0674
Photo-oxidant formation	P (%)	3.4	3.6	25.4	0.0056 –
kg ethylene eq	T (%)	96.6	96.4	74.6	0.0072
Human toxicity	P (%)	4.8	5.6	39.3	0.6606–
kg 1,4-DB eq	T (%)	95.2	94.4	60.7	1.0356
Freshwater Aquatic Ecotoxicity	P (%)	3.1	3.1	13.8	0.0622 –
kg 1,4-DB eq.	T (%)	96.9	94.9	86.2	0.0700
Marine Aquatic Ecotoxicity	P (%)	3.1	3.1	23.1	980.9210 –
kg 1,4-DB eq.	T (%)	96.9	96.9	76.9	1221.2500
Terrestrial Ecotoxicity	P (%)	3.1	3.1	14.6	0.0275 –
kg 1,4-DB eq.	T (%)	96.9	96.9	85.4	0.0311
Ozone layer depletion	P (%)	3.1	3.1	88.3	1.04×10^{-7} –
kg R11 eq.	T (%)	96.9	96.9	11.7	8.58×10^{-7}

[1] P : % contribution from the processing of materials on site
[2] T : % contribution from transport of materials to the recycling site

Strengthens and weakness of the whole study, general comments	Sensitivity analysis	$S_{ROBUSTN}$ = 3
Subject to independent review?	In accordance with the ISO14040 standard, this study has been conducted under peer review by an external reviewer	S_{REVIEW} = 5
		22.33

		Scoring
Authors	Blengini G.A. and Garbarino E.	
Year	2010	
Title	Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix.	
Reference	Journal of Cleaner Production 18, 1021–1030	
Type of study	According to ISO 14040-44 (2006)	S_{SCOPE} = 3
Scope	To what extent recycled aggregates can complement natural aggregates in a sustainable supply mix (SSM) for the construction industry To identify and quantify energy and environmental loads, under different assumptions relevant to delivery distances, quality of recycled aggregates, local availability of natural aggregates and geographical coverage of market demand	
Functional unit	1 t of collected and recycled C&DW	
System boundaries		
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Data about 89 recycling plants, including technological features, output and physical–mechanical characteristics of recycled aggregate	S_{DATA} = (5+5+3) = 4.33
Calculation methodology/ programme	A combined Geographical Information System (GIS) and Life Cycle Assessment (LCA) model was developed using site-specific data and paying particular attention to land use, transportation and avoided landfill LCA modelling was performed using the SimaPro 7 tool (Simapro, 2006) and secondary data were retrieved from the Ecoinvent 2.0 database (Ecoinvet, 2006).	
Impact assessment categories/methods	IMPACT 2002+ (Jolliet et al., 2003; Humbert et al., 2005) and ECO-INDICATOR 99 (Goedkoop and Spriensma, 1999) methodologies 14 midpoint indicators: • human toxicity (HT) (carcinogen and noncarcinogen effects), • respiratory effects caused by inorganics (RI), • ionizing radiation (IR), • ozone layer depletion (OLD), • photochemical oxidation (PO), • aquatic ecotoxicity (AE), • terrestrial ecotoxicity (TE), • aquatic acidification (AA), • aquatic eutrophication (AEu), • terrestrial acidification and nitrification (TAN), • land occupation (LO),	$S_{IMPACTS}$ = 3

	• global warming (GW), • non-renewable energy (NRE) • mineral extraction (ME). 4 damage (endpoint) indicators: human health (HH), ecosystem quality (EQ), climate change (CC) and resources (R).	
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material; improvement options)	LCA was helpful to bring into a comprehensive model, and with a life cycle perspective, data and knowledge relevant to all the key elements in the C&DW recycling chain, including (1) collection, (2) recycling, (3) avoided landfill, (4) transportation, (5) avoided quarrying. 13 of 14 indicators have showed that avoided impacts are higher than induced impacts. The only indicator for which the impacts outweigh the environmental gains is HT and this can be ascribed to re-melting of steel scraps via electric arch process. Among other midpoint indicators, the net avoided impacts in the C&DW recycling chain correspond to 14 kg/t of avoided carbon dioxide emission and saving of 250 MJ/t of non-renewable energy.   **Fig. 5.** Normalised midpoint indicators in the life cycle of 1 t C&DW. The analysis of the contribution of subsystems in the recycling chain confirmed the key role of transportation, therefore emphasising the need for a deeper understanding and an efficient management of the collection and distribution network, as excessive distances, or use of inefficient collection systems, might compromise the overall environmental performance. The sensitivity analysis confirmed that transportation distance of recycled aggregate should increase 2–3 times before the induced impacts outweigh the avoided impacts  *Influence of recycled aggregate delivery distances: net environmental gains in the recycling chain in comparison with the baseline scenario where RA distance is assumed to be 70% of NA distance.* From an economic viewpoint, the costs of C&DW recycling in the study area are totally covered by private operators which save money for not having to pay landfill taxes and obtain an income for selling recycled products. The methodology for incorporating land use impacts in LCA needs further investigation.	S_{OUTC} = 3
Strengthens and weakness of the whole study, general comments	Sensitivity analysis on transportation distances	$S_{ROBUSTN}$ = 5
Subject to independent review?		S_{REVIEW} = 3
		21.33

		Scoring
Authors	Chowdhury R., Apul D. and Fry T.	
Year	2010	
Title	A life cycle based environmental impacts assessment of construction materials used in road construction	
Reference	Resources, Conservation and Recycling 54, pp. 250–255	
Type of study		S_{SCOPE}= 3
Scope		
Functional unit	A 1-kilometer-long section of road 2.5 meters wide and 600 mm thick. The periods of analysis are 20, 100 and 500/infinity years.	
System boundaries (stages and process cut-off)	System boundary of a material in this study included the production and transportation of the material and associated electricity and oil consumption  **Fig. 1.** A schematic representation of the system boundary in the present study. (a) System boundary for a material production and (b) system boundary for the transportation. (Note: dashed arrows indicate no transportation is required to proceed from one process to the other). **Main assumptions** Construction activities such as excavation and compaction as well as maintenance were not considered since it was assumed that environmental emissions and cost associated would be similar for maintenance work. It was assumed that industrial byproducts and natural aggregates were transported from source to site by 32 ton trucks for 50km and 100 km, respectively.	
Assumptions (e.g. allocation)		
Data sources and quality **1. Raw materials production phase** **2. Production phase** **3. Road construction phase** **4. Use phase** **5. Maintenance and operation phase** **6. End of Life phase**	Material production and transportation phase Energy production (only coal combustion electric generation) Oil extraction, refining and combustion Energy consumption and emission from transportation are collected from Stripple (2001). Electricity inventory data were taken from a US coal fired based energy plant described in Spath et al. (1999). Inventory data for natural aggregate was obtained from Stripple (2001).	S_{DATA} = (3+3+3)/3= 3
Calculation methodology/ programm(e	This paper used a web based model BenReMod (http://benremod.eng.utoledo.edu/BenReMod/ which is developed in the same research program.	
Impact assessment categories/methods	Characterization factors for toxicity assessment potentials are from Huijbregts et al. (2000) and from the database of CMLCA (2008). Characterization factors for acidification potential and global warming potential are taken from Houghton et al. (2001). LCIA according to CML and Houghton et al. (2001) and Huibregts et al. (2000) - Energy consumption - Acidification potential AP (classification B) - Global warming potential GWP (classification A) - Human toxicity potential HTP - Aquatic ecotoxicity potential FAETP - Aquatic sediment ecotoxicity potentialFSETP - Terrestrial ecotoxicity potential TETP	$S_{IMPACTS}$ = 5
Conclusions (e.g. most important life lifecycle phases; most important drivers to impacts - process/material;	The study compared the replacement of natural aggregates (NA), with three industrial by-products (fly ash, bottom ash and recycled concrete pavement) in road construction. The study found the three by-products was cheaper, but each had both higher and lower environmental impact than the natural aggregates: **Fly ash:** Has a significant higher impact than natural aggregate on both terrestrial, freshwater	S_{OUTC} = 5

improvement options)	aquatic and freshwater sediment toxicity potential (TETP 20/100, FAETP 20/100/inf and FSETP 20/100/inf) because of leaching of heavy metals to soil. Air emission of PM10 from the production was also significantly higher than from natural aggregate. **Coal bottom ash:** Has a significant higher impact than NA on both human and terrestrial toxicity potential on an infinity time horizon. **Recycled concrete pavement (RCP):** Has a higher energy use and a significantly higher impact on GWP and acidification than natural aggregate. Furthermore the production of RCP causes a higher air emission (NO_X, SO_2, CO and CO_2) than NA. The study also calculated some rules-of-thumb: • With a ratio of transportation distance 2:1 natural aggregate versus industrial by-products, the industrial by-products have an advantage over natural aggregate as regard to energy, GWP and acidification • The natural aggregate based road has smaller impacts on energy, GWP and acidification compared to recycled concrete pavement (can change is the transportation scenario is changed) • If the transportation distances is more than 1:3 (natural aggregate versus fly ash and bottom ash), fly ash and bottom ash have higher impacts in energy, GWP and acidification. • Recycled concrete pavements in general was found to have the highest concerning GWP and acidification • If the ratio of transportation distance between Recycled concrete pavements is more than 4 for the natural aggregate (1:4) then the natural aggregate has the highest impacts related to GWP, energy and toxicity. The authors conclude: "*quantitative and comparable life cycle assessment results on road construction materials are essential first steps towards making informed decisions towards more sustainable practices in road construction*"	
Strengthens and weakness of the whole study, general comments		$S_{ROBUSTN}$ = 1
Subject to independent review?		S_{REVIEW} = 3
		20

III.3 Technical analysis

Table III.6: Summary of leaching criteria for waste/by-product derived aggregates in different EU Member States. (continued on next page)

Country:	Austria			Belgium	Denmark			Finland				France					
Region:				Vlanderm								Level 1A	Level 1B	Level 1C	Level 1	Level 2A	Level 2B
Category:	A+	A	B	Unbound	Cat. 1	Cat. 2	Cat. 3	Covered	Paved	Covered	Paved	80%	95%	100%	Exclusion		
Materials	C&DW			General	Residues			C&DW		Ashes							
Test:	EN 12547-4			CEN/TS 14405	EN 12457-1			CEN/TS 14405				EN 12457-2/EN 12457-4					
L/S (l/kg)	10	10	10	10	2	2	2	10	10	10	10	10	10	10	10	10	10
Unit:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Chloride	800	800	1000		600 (3000)	600 (3000)	12000	800	800	800	2400	800	1600	2400	15000	10000	5000
Fluoride	10	10	15					10	10	10	50	10	20	30	150	60	30
Sulfate	1500	2500	5000		1000 (4000)	1000 (4000)	16000	1000	3000	1000	10000	1000	2000	3000	20000	10000	5000
Arsenic	0.5	0.5	0.5	0.8	0.032	0.032	0.2	0.5	0.5	0.5	1.5	0.5	1	1.5	2	0.8	0.5
Barium	20	20	20		1.2	1.2	16	20	20	20	60	20	40	60	100	56	28
Cadmium	0.04	0.04	0.04	0.03	0.008	0.008	0.16	0.02	0.02	0.04	0.04	0.04	0.08	0.12	1	0.32	0.16
Chromium (tot)	0.3	0.5	0.5	0.5	0.04	0.04	2	0.5	0.5	0.5	3	0.5	1	1.5	10	4	2
Copper	0.5	1	2	0.5	0.18	0.18	8	2	2	2	6	2	4	6	50	50	50
Mercury	0.01	0.01	0.01	0.02	0.0004	0.0004	0.004	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.2	0.08	0.04
Molybdenum								0.5	0.5	0.5	6	0.5	1	1.5	10	5.6	2.8
Nickel	0.4	0.4	0.6	0.75	0.04	0.04	0.28	0.4	0.4	0.4	1.2	0.4	0.8	1.2	10	1.6	0.8
Lead	0.5	0.5	0.5		0.04	0.04	0.4	0.5	0.5	0.5	1.5	0.5	1	1.5	10	0.8	0.5
Antimony	0.06	0.06	0.1					0.06	0.06	0.06	0.18	0.06	0.12	0.18	0.7	0.4	0.2
Selenium	0.1	0.1	0.1		0.04	0.04	0.12	0.1	0.1	0.1	0.5	0.1	0.2	0.3	0.5	0.5	0.4
Zinc	4	4	18	2.8	0.4	0.4	6	4	4	4	12	4	8	12	50	50	50
TDS	4000	4000	8000									4000	8000	12000	60000		
DOC	500	500	500					500	500	500	500						
pH	7.5-12.5																
Reference	A	A	A	A	C	C	C	D	D	D	D	F	F	F	F	F	F

Country:	Germany			Italy	Netherlands		Spain			Sweden		EU
Region:	Z0/Z1.1	Z1.2	Z2				Cantabria	Basque	Catalunya			
Category:					300mm/y	6mm/yr				Free Use	Landfill	Landfill
Materials	Soils			Residues	All materials		Slags			Waste		Inert waste
Test:	EN 12457-2			EN 12457-2	CEN/TS 14405		EN 12457-4		DIN 38414-54	CEN/TS 14405		EN 12457-2 / CEN/TS 14405
L/S (l/kg)	10	10	10	10	10	10	10	10	10	10	10	10
Unit:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Chloride	300	500	1000	1000	616	8800	800			130	11000	800
Fluoride				15	55	1500	10	18				10
Sulfate	200	500	2000	2500	1730	20000	1000	377		200	8500	1000
Arsenic	0.14	0.2	0.6	0.5	0.9	2	0.5		1	0.09	0.4	0.5
Barium				1	22	100	20	17				20
Cadmium	0.015	0.03	0.06		0.04	0.06	0.04	0.009 (0.6)	1	0.02	0.007	0.04
Chromium (tot)	0.125	0.25	0.6	0.5	0.63	7	0.5	2.6	5	1	0.3	0.5
Copper	0.2	0.6	1	0.5	0.9	10	2		20	0.8	0.6	2
Mercury	0.005	0.01	0.02	0.01	0.02	0.08	0.01		0.2	0.01		0.01
Molybdenum					1	15	0.5	1.2				0.5
Nickel	0.15	0.2	0.7	0.1	0.44	2.1	0.4	0.8	5	0.4	0.6	0.4
Lead	0.4	0.8	2	0.05	2.3	8.3	0.5	0.8	5	0.2	0.3	0.5
Antimony					0.16	0.7	0.06					0.06
Selenium				0.1	0.15	3	0.1	0.007 (0.2)				0.1
Zinc	1.5	2	6	30	4.5	14	4		20	1	3	4
TDS							4000					
DOC							500					500
pH	6.5-9.5	6-12	5.5-12	5.5-12								
Reference	G	G	G	A	H	H	A	A	A	I	I	J

The references for the above table are as follows:

A Böhmer, S., Moser, G., Neubauer, C., Peltoniemi, M., Schachermayer, E., Tesar, M., Walter, B., Winter, B. (2008): AGGREGATES CASE STUDY, Final Report referring to contract n° 150787-2007 F1SC-AT "Aggregates case study – data gathering" (study commissioned by JRC-IPTS), Vienna.

C Statutory Order No. 1662 of 21 December 2010 on recycling of residual products and soil in building and construction works and on recycling of sorted, unpolluted C&D waste. Values in parentheses are "temporarily" increased limit values for MSWI bottom ash.

D Finnish Government Decree 591/2006 pm reuse of some waste materials in earth construction.

F Sétra (2011): Acceptabilité de matériaux alternatifs en technique routière. Évaluation environmentale. Guide Méthodologique. Service d'etudes sur les transports, les routes et leurs aménagements. Bagneux Cedex, France.

G LAGA (2004): Working Group of the German Länder under Waste Issues: Länderarbeitsgemeinschaft Abfall, Eckpunkte (EP) der LAGA für eine "Verordnung über die Verwertung von mineralischen Abfällen in technischen Bauwerken", Stand 31.08.2004.

H SQD (2007): Soil Quality Decree. Staatscourant 20 December, Nr. 247, 67 – 90, The Netherlands.

I Swedish EPA (2010): Återvinning av avfall i anläggningsarbeten Handbok 2010:1. ISBN 978-91-620-0164-3.pdf. Naturvårdsverket, Stockholm, Sweden

J CEC (2003): Council Decision 2003/33/EC of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 and Annex II to Directive 1999/31/EC. Official Journal of the European Communities, 16.1.2003, L11/27-49.

The data in the above table has been adapted from Umweltesbundesamt, 2008. Other leaching criteria not included in the table but that were specified by a limited number of Member states include; bromide, ammonium, nitrate, cyanide, Sodium, Beryllium, Manganese, Tin, Vanadium, Cobalt, Chromium (VI), Phenol index, HydroCarbon (HC) index, Chemical Oxygen Demand (COD), Electrical Conductivity (EC) and Polycyclic Aromatic Hydrocarbon (PAH) content.

Table III.7: The 27 products in the family of common cements

Table 1 — The 27 products in the family of common cements

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass[a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calca-reous				
			K	S	D[b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	0-5
		CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	0-5
		CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	6-20	–	0-5
		CEM II/B-L	65-79	–	–	–	–	–	–	–	21-35	–	0-5
		CEM II/A-LL	80-94	–	–	–	–	–	–	–	–	6-20	0-5
		CEM II/B-LL	65-79	–	–	–	–	–	–	–	–	21-35	0-5
	Portland-composite cement[c]	CEM II/A-M	80-88	← 12-20 →									0-5
		CEM II/B-M	65-79	← 21-35 →									
CEM III	Blast furnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement[c]	CEM IV/A	65-89	–	← 11-35 →					–	–	–	0-5
		CEM IV/B	45-64	–	← 36-55 →					–	–	–	0-5
CEM V	Composite cement[c]	CEM V/A	40-64	18-30	–	← 18-30 →			–	–	–	–	0-5
		CEM V/B	20-38	31-49	–	← 31-49 →			–	–	–	–	0-5

[a] The values in the table refer to the sum of the main and minor additional constituents.

[b] The proportion of silica fume is limited to 10 %.

[c] In Portland-composite cements CEM II/A-M and CEM II/B-M, in pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for examples, see Clause 8).

Additional references for the supporting documents of the Preliminary report

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