INNOVATIVE METHODOLOGIES TO ACCOUNT AND OPTIMISE ROAD SUSTAINABILITY IN PAVEMENT DESIGN

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ABSTRACT

Due to economic, political and ecological reasons, recent years have seen the need for a change in road infrastructure design concepts to focus on optimising the use of resources and reduce waste and pollution. Furthermore, governments will be increasingly required to submit regular Greenhouse Gas (GHG) emission accounts as part of their international commitment, in particular under the United Nations (UN) Climate Change Convention. Consequently, the road sector is reviewing current practices to account and reduce carbon emissions, and the Life Cycle Approach has been accepted as a robust method of measuring carbon footprint. On the other hand, the introduction of performance specifications and end-product testing has helped designers to optimise pavement and materials requirements, to ensure construction quality and to improve future performance and sustainability. This paper outlines the common methodology of road carbon footprinting and presents the results obtained by using performance specifications during road design and construction. The study also shows the application of these tools in sustainable construction assessment schemes and presents the resources available to undertake such an analysis. Some world-wide recognized tools and datasets developed to facilitate the measurement are reported together with results from case studies of using innovative tools and design approaches. Finally, the CO2 output of a number of completed projects is compared, and an investigation made to seek the causes of any differences.

Keywords: performance specification, pavement design, carbon footprinting, LCA.

INTRODUCTION

Due to past and current global greenhouse gas emissions we all are committed to decades of climate change (OECD, 2010). Consequently, we not only need to reduce our global GHG emissions to minimise the risk of the most severe impacts from occurring, but we now also need to put in place effective long-term adaptation measures.

Beyond the 2040s, the severity of climate change will depend on how successful global action to reduce global GHG emissions is. Nevertheless, it is clear that adaptation will present a long-term challenge to the country and its infrastructure. The UK has experience of the sorts of extreme weather events we might expect more of in the future. In August 2003 the highest daily temperature for England of 38.5ºC was recorded by the Met Office (Met Office, 2011) whilst in the summer of 2007, severe floods affected the country. The general trend shows the climate getting hotter, with temperatures rising by up to 1ºC across the UK since the 1970s (UK Climate Projections, 2009). Sea level has also risen by about 1mm/yr in the 20th century, with higher rates for the 1990s and 2000s (UK Climate Projections, 2009). Before 2001, the Thames Barrier was raised on average three times per year, compared with an average of six times per year between 2001 and 2008 (Environment Agency, 2012): it is likely that the rise in sea level has contributed to this increase.

Climate change resulting from human activities is recognised as one of the most urgent environmental issues facing the global community. New structural design approaches developed mainly in recent years (Highways Agency, 2006), together with the development of innovative construction technologies (e.g. use of Polymer Modified Bitumen), permit optimisation of material usage (i.e. pavement layer thickness reduction or improved material durability) and to achieve higher and more reliable quality control. This has been possible by developing constructive technologies and design approaches based on achieved performance, mainly of a mechanical nature, to substitute requirements based on compositional prescription. As a consequence of this, an increase of materials' mechanical performance and an overall enhancement from economic and environmental perspectives of the construction process, especially where operational conditions were complex and/or when economic and/or environmental restrictions, was observed.

The main aim of this paper is to describe techniques able to enhance the sustainability aspects in pavement design of road pavements. Within the first part of this publication the Authors intend to provide an overview of the most innovative design approaches currently in use, focusing attention on environmental advantages gained by their application and by using innovative construction techniques. This includes a series of case studies concerning important results achieved. In the second part of this paper, a methodology aimed at measuring the carbon footprint of road construction is reported and an innovative evaluation tool (CHANGER) is described. A number of real examples of applying techniques for carbon footprint of road construction evaluation are reported.

INNOVATIVE PAVEMENT DESIGN APPROACHES

Pavements can be broadly classified into flexible (asphalt over unbound or hydraulically bound foundation), rigid (reinforced or un-reinforced concrete slabs over typically bound foundation) and composite (asphalt surfacing over hydraulically bound base over foundation). Traditionally, the UK pavement specifications were based on a recipe approach, where selected materials are laid and compacted with specified plant in a specified manner to achieve a minimum level of performance. However, performance specifications and end-product testing have gradually been introduced to the UK standards in order to optimise the range of materials used (including recycled, locally won, and industrial by-products), to improve both quality and sustainability. Therefore, the impact of improved material properties on the pavement design thickness and expected life can be considered. This section describes the two specifications HD26/06 (Highways Agency, 2006) and IAN73 (Highways Agency, 2009) and focus on the environmental benefits coming from applying these new design procedures.

FOUNDATION DESIGN

UK pavement foundation design was based primarily on the use of the California Bearing Ratio (CBR) to characterise the subgrade, capping and subbase materials (Highways Agency, 1994). The thicknesses of subbase and capping materials were determined from the subgrade CBR to achieve a "standard pavement foundation", following a specific chart. The foundation design was independent of traffic levels and had no impact on upper pavement bound layer thicknesses. The benefit of using a stiffer foundation below the asphalt did not reduce the upper pavement layer thickness in this design method; even though it would improve pavement support and overall bearing capacity.

Although CBR has been correlated with pavement performance in many countries over many years and provides a trusted empirical indicator of material behaviour, the use of CBR as a performance parameter is widely acknowledged as being not wholly satisfactory (Brown 1996). Furthermore, the need for a fundamental engineering property (such as stiffness) to describe the unbound and weakly bound materials has become important for use in analytical and mechanistic design methods. The stiffness modulus of a pavement foundation is a measure of the quality of support which is provided to the overlying asphalt or concrete layers. Advances in the in-situ testing of pavement foundation materials enabled a performance based specification for road foundation layers to be introduced in the UK, hence facilitating the use of secondary aggregates, marginal materials and stabilised ground.

The Falling Weight Deflectometer (FWD) and Light Weight Deflectometer (LWD) measure the composite foundation stiffness under a transient load pulse, which is applied to the ground by dropping a weight onto a bearing plate via a rubber buffer (see Figure 1). The deflection of the ground is measured and combined with the applied load to calculate the stiffness using conventional Boussinesq analysis (Hakim, 2002). The LWD is a hand held device and hence more practical for compliance monitoring during foundation construction.

Figure 1 Falling Weight Deflectometer (FWD) and Light Weight Deflectometer (LWD) Tests on a foundation

The Springbox was developed by URS and is currently specified in IAN 73 (Highways Agency, 2009) for use to assess the stiffness and deformation properties of unbound and weakly bound materials in the laboratory. The equipment enables a realistic material compaction level to be applied during preparation, followed by repeated vertical loading with various magnitudes to represent trafficking during construction with appropriate pavement confinement. The device can be used to characterise the fundamental material properties, considering various mixtures with different moisture contents and binder types, as well as ageing, temperature and saturation levels, for use in the analytical and mechanistic pavement design approaches. One of the objectives of this new approach is to allow a wider range of materials to be used for capping and subbase construction, based on their mechanical properties, with the general move towards end-product based specifications.

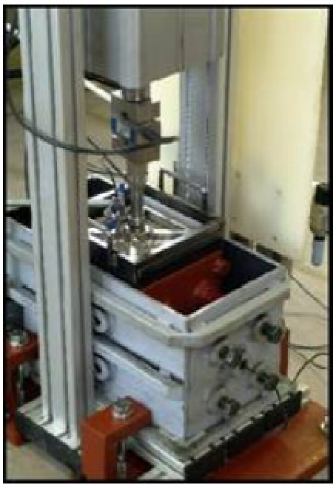

Figure 2 The Springbox Test

The new UK pavement design method (Highways Agency, 2009) considers four foundation classes defined by the long-term in-service "Foundation Surface Modulus", obtained applying a known load at top of the foundation (e.g. FWD testing):

- Foundation Class 1, Foundation Surface Modulus considered: 50MPa (typically capping layer over subgrade).
- Foundation Class 2, Foundation Surface Modulus considered: 100MPa (typically unbound subbase over subgrade).
- Foundation Class 3, Foundation Surface Modulus considered: 200MPa (weakly bound subbase over subgrade).
- Foundation Class 4, Foundation Surface Modulus considered: 400MPa (strongly bound subbase over subgrade).

The design charts are then used to calculate the layer thickness over a given subgrade stiffness to meet the specified Foundation Class. A demonstration area is constructed and tested to assess the actual expected foundation performance for the site under consideration; and finally end-product testing is carried out to ensure that the foundation design requirements are met during construction. Figure 3 shows a typical design chart for Foundation Class 2.

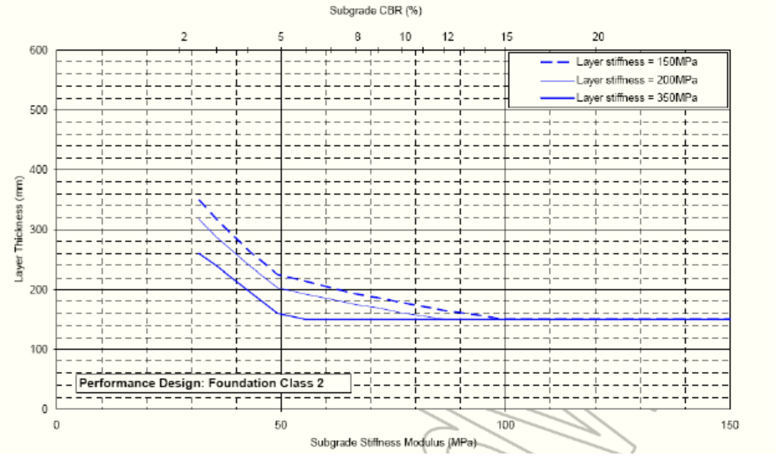

Figure 3 Foundation performance based design – Foundation Class 2 (Highways Agency 2009)

Figure 3 shows that 225mm of unbound subbase (typically with a layer stiffness of 150MPa) over a subgrade with 5% CBR (stiffness modulus of 50MPa) is needed to meet the Foundation Class 2 requirements. However, a subbase thickness of 160mm with a layer stiffness of 350MPa (typically stabilised) can also meet the above foundation class.

Therefore, using marginal, recycled and secondary aggregates with the appropriate binder content to achieve the subbase layer stiffness in a performance specification can provide a reduction in foundation thickness , potentially leading to cost and sustainability benefits, provided end-product performance testing (e.g. LWD) is carried out. This option was not permitted in the previous design standard and previous pavement design approaches. An additional advantage of introducing the four foundation classes is the possible reduction of the thickness of upper pavement layers to account for the contribution of stronger/stiffer foundations. The design standard still permits the use of recipe foundation design, but with thicker construction compared with the performance design to account for materials variability. This option would be used on smaller projects where the cost of additional materials testing is not justified.

HYDRAULICALLY BOUND MIXTURE (HBM)

The new UK pavement design standard allows the use of a wide range of Hydraulically Bound Mixtures (HBM) with cement, lime, slag and fly ash binders with marginal, recycled and secondary local aggregates. Their fundamental properties are assessed during the design and monitored during construction. HBM can be used in the foundation to meet the above foundation classes or as a lower base in flexible composite constructions, where the HBM base thickness and category are specified during the design stage and monitored for compliance during the construction stage. HBMs are categorised according to their compressive and tensile strengths and according to aggregate types used (Cement Bound Granular Mixtures (CBGM), Slag Bound Mixtures (SBM) and Fly Ash Bound Mixtures (FABM)).

ASPHALTIC MATERIAL

UK asphaltic materials include various types of mixtures such as Hot Rolled Asphalt (HRA), Dense Bituminous Macadam (DBM) and High Modulus Base (e.g. EME2), having different mix designs, stiffnesses and binder properties.

The design approach (Highway Agency 2006) allows the use of thinner constructions if stiffer asphaltic materials are used (see Figure 4). The asphaltic mixtures are specified in terms of laboratory stiffness during the design stage and monitored for compliance during construction by testing samples extracted from the pavement. Additional testing to assess the deformation resistance, water sensitivity and durability of the asphaltic mixtures are also recommended during the mix design stage. Other mixtures, such as those containing percentages of reclaimed asphalt and cold/hot in-situ/ ex-situ recycled materials, are permitted, provided their properties are assessed and tested. The use of recipe mixtures is also permitted in the current standard if required.

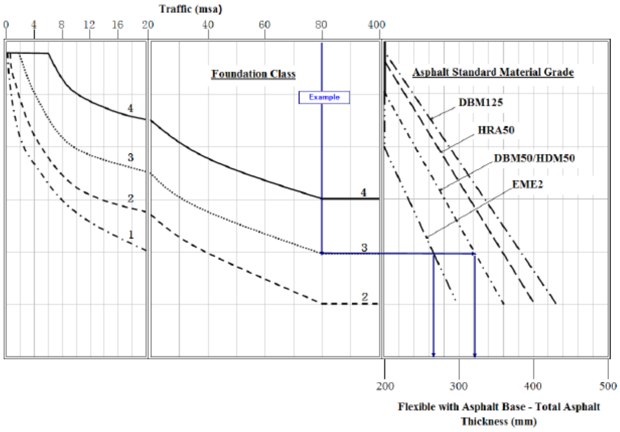

Figure 4 Extract from the UK flexible pavement design guide (Highway Agency 2006)

Figure 4 shows an asphalt thickness of 265mm incorporating EME2 binder/base compared with 320mm incorporating DBM50 binder/base over foundation class 3, to carry a traffic loading of 80 millions of equivalent standard axle load (msa). Another advantage of the design method is the reduction in asphalt thickness when stiffer (e.g. stabilised) foundation is specified. Figure 4 indicates an asphalt thickness incorporating 280mm of DBM50 binder/base over Foundation Class 4, compared with 360mm over Foundation Class 2 to carry future traffic of 80 msa.

PAVEMENT QUALITY CONCRETE

The use of jointed reinforced/un-reinforced concrete pavements for new construction is restricted due to high maintenance cost, construction delay, noise and poor ride quality. However, continuously reinforced concrete pavements (CRCP) and pavements with a continuous reinforced concrete base (CRCB) with asphalt surfacing are recommended when heavy traffic and poor subgrade are encountered, if construction and life cycle costs are advantageous. The recent design standard (Highways Agency, 2006) has introduced various concrete grades with flexural strength of 4.5, 5.0, 5.5 and 6.0 MPa to allow the use of wider design options. The previous design was based on a single concrete compressive strength, and limited to 40MPa.

ENVIRONMENTAL BENEFITS

Potential benefits to the environment from using the new standard can be expected as a result of a number of factors, such as: using marginal, secondary, local and recycled aggregates with a wider range of binders including slag and fly ash in foundation design, reducing foundation thickness when stabilised, and using thinner upper bound layers with a stiffer foundation. Advantages of using thinner but stiffer pavements include: reducing aggregates and binder use; reducing aggregate production (crushing, processing and transportation); reducing the effort of mixing, transporting, laying and compacting the mixes and associated vehicle movements during construction; reducing fuel cost and CO_2 emissions; and reducing project time, resources requirements, noise and disruption to the public.

The performance testing improves construction quality and provides better material durability with longer service life and/or less maintenance work. This helps to reduce the requirement for premium aggregates for maintenance or resurfacing works.

LIFE CYCLE ASSESSMENT OF ROAD PAVEMENTS

A life-cycle assessment (LCA, also known as life-cycle analysis, ecobalance) is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). LCA can help avoid a narrow outlook on environmental concerns by (US Environmental Protection Agency, 2010, ISO14040 2006)):

- Compiling an inventory of relevant energy and material inputs and environmental releases;
- Evaluating the potential impacts associated with identified inputs and releases;
- Calculating, presenting and interpreting the results to help make a more informed decision.

The life cycle of a road construction can be categorized into four phases as follows (notably, transport is integrated in all phases, and the maintenance/ rehabilitation activities can repeat some, or all, of previous phases):

- Raw materials sourcing and products manufacture (e.g. asphalt, concrete);
- Transport of raw materials to mixing plant, and products to site;
- Construction on site, including machinery use and office hire;
- Maintenance and rehabilitation, including recycling or disposal of unserviceable materials.

Broadly, the techniques required in carbon footprinting are similar to those of energy analysis and life cycle assessment (LCA).

Carbon footprinting is a measure of the carbon dioxide (CO_2) and other GHGs, which tend to be combined into a CO2 equivalent (CO2-eq) for measurement purposes, of an activity or product that allows the sources of the impacts to be understood, investigated and managed. Decisions and assumptions have to be made about the nature of the systems being modelled, during which the GHG emissions from each individual process will be quantified and compiled. This can be undertaken for a business-as-usual scenario that establishes an equivalent carbon dioxide (CO_2-eq) baseline, or for several scenarios for comparison.

A business advantage of taking proactive steps to measure and reduce the GHG emissions of road construction is that more and more international finance institutions are progressively including compulsory GHG emissions assessment in their tendering procedures (IRF, 2010).

Representing around 15% of global greenhouse gas (GHG) and 23% of energy-related carbon dioxide (CO_2) emissions (OECD, 2010), the transport sector clearly has the scope and means to make a significant contribution in terms of championing more eco-friendly techniques and technologies. Alongside other industries, the road sector has developed an array of emission assessment tools, as part of this endeavor and as an effective way to help translate into reality the low carbon transportation strategies set up by governments. A number of tools and datasets have been developed over the past decade, an example is CHANGER.

CHANGER: A Tool to Estimate Carbon Footprinting

CHANGER, the Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emissions for Roads, was developed by the International Road Federation (IRF) and the first version was released in November 2009. The model was developed with a view to introducing an IRF standard and certification. The goal of this tool is multifaceted (Zammataro et al., 2011):

- To facilitate an environmental analysis of road projects;
- To provide a basis for comparative analysis of various road laying techniques and materials;
- To optimise site supply schemes with respect to choice of suppliers, delivery locations and transport modes;
- To enable an estimation of the carbon footprint of road construction activities.

The tool development, in partnership with Ammann, Colas and URS, undertakes an iterative approach including data sourcing, initial analysis, feedback to data provider, and review of calculations, according to (ISO 14044, 2006).

The tool takes into account a range of emissions sources during project life, compliant with the Intergovernmental Panel on Climate Change guidelines, and analyses at a project level to benchmark the carbon footprint per km of road construction. The datasets and the calculation have been validated by the Traffic Facilities Laboratory of the Swiss Federal Institute of Technology (Bueche and Dumont, 2009).

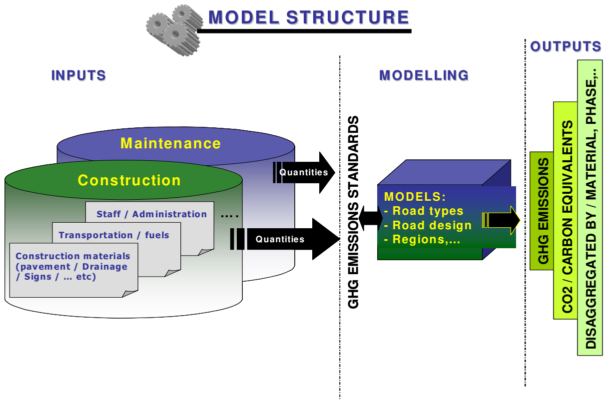

Figure 5 model Structure of CHANGER (source: (IRF, 2007))

CHANGER adopts a typical process-based modelling approach (Figure 5). The calculation model is based on a set of equations that enable accurate estimation of overall GHG emissions (outputs) generated by each identified and quantified source (inputs). CHANGER currently comprises two main modules: Preconstruction and Pavements. Data will be sourced for the following activities:

- Preconstruction: site clearance, cut and fill, deforestation;
- Onsite energy (electricity, fossil fuels) consumption;
- Materials quantity;
- Transport mode and distance;
- Construction vehicles and equipments;

The effects of three GHGs have been considered in the calculation: carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), all converted to the carbon dioxide equivalent (CO_2-eq). The model does not account for the loss of CO_2 absorption by removal of trees or other land use change.

Case Studies

The embodied energy and carbon of materials varies across regions and industry sectors. CHANGER has been applied to major road projects in different technical and economic environments for testing, calibration and improving functionality. The case studies include a UK trunk road widening and a Public Private Partnership (PPP) highway construction in United Arab Emirates (UAE).

UK trunk road widening

The project road was a single-lane trunk road located in the UK which carried up to 25,300 vehicles per day, of which approximately 15% are heavy goods vehicles (HGV). The existing road presents many junctions and access roads, giving rise to daily congestion and a poor safety record. The UK Highways Agency proposed a new 28km long dual two-lane carriageway, with eight grade separated junctions. By using the innovative pavement design approach previously detailed, a composite pavement construction of 180mm asphalt material over 200mm HBM base over 250mm stabilised Class 3 foundation was considered for the majority of the road length (Figure 6). This pavement option improved project sustainability compared with the conventional full depth asphalt construction over granular sub-base. Stabilising the foundation using local materials negated the need to import good quality aggregate for the subbase, and improved the foundation bearing capacity which led to a reduction in pavement thickness. In order to better control pavement quality, end-product performance testing were used to ensure that the design parameters were met during construction.

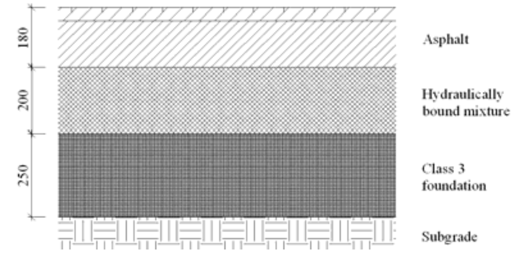

Figure 6 As-built pavement design in UK trunk road widening case study

The project data (as-built) including pavement, geotechnical and drainage were collected from design consultants, over a period of nine months between April and December 2009 (i.e. quarter of the construction period). These data were run through CHANGER. In summary, the results indicated:

- The construction activities released a total CO_2-eq of 20,788t;
- As for comparison, the same data when run through the UK Highways Agency's carbon calculator, indicated a CO_2-eq of 17,252t. In other words, there is a 20% difference between results from the two calculators;
- Provided the nine-months data (Apr-Dec/2009) available represent one third of the project's overall activities, this trunk road widening (28km long) would release about 2,047t CO_2-eq/km construction.

UAE PPP highway construction

The Department of Transport of the Emirate of Abu Dhabi issued a tender to upgrade an existing 250km long road, to a four-lane dual carriageway. URS was committed for one of the bidding consortia to optimise the solution considering project contract performance requirements, whole life cost, constructability and sustainability. Figure 7-right shows a pavement option incorporating standard asphalt construction in accordance with the local standards, while Figure 7-left shows a proposed alternative pavement option enhancing the use of local materials in cement-bound base and using an analytical design approach and end-product performance testing to better control the pavement quality.

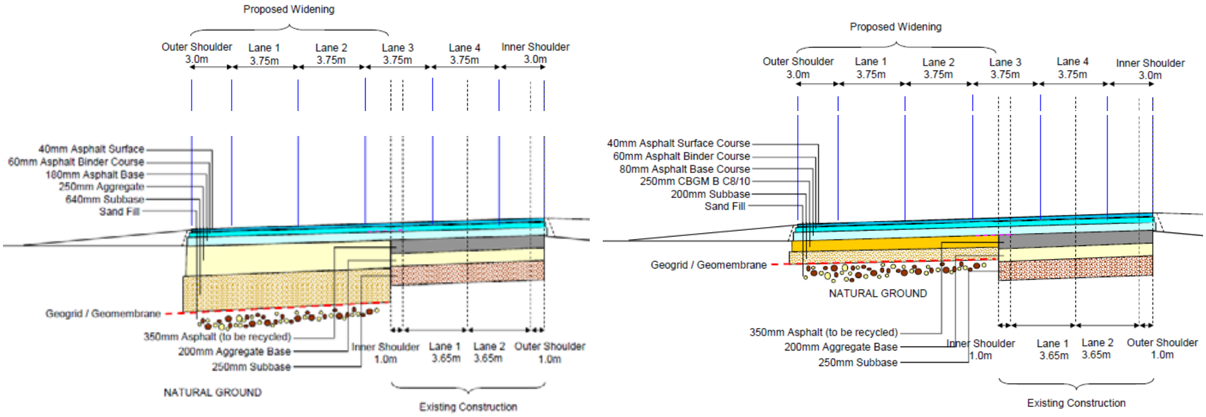

Figure 7 Different pavement constructions in UAE: Conventional Pavement Design (right) and As-built Pavement Design (left)

The CO_2 results from CHANGER for design options A and B are presented in Table 1. In summary, Option B saves about 266,710t of CO_2 compared to Option A (11% less). The saving comes from transport (164,332t less) and material manufacture (123,286t less), which is slightly offset by site activities (20,896t more). In both options, the embodied CO_2 of materials (including manufacture and upstream processes such as raw materials provision, transport, etc.) accounts for some 52% of the project total, thus representing the 'hot spot' in this project.

Table 1 Carbon Footprint of UAE Pavement Designs

	Unit	Material embodied	Transport	Construction	Total
Option A	t CO_2	1,254,509	792,185	359,705	2,406,400
Option B	t CO_2	1,131,223	627,853	380,601	2,139,690
Savings (A-B)	t CO_2	123,286	164,332	-20,896	266,710

ENVIRONMENTAL BENEFITS OF LCA IN PAVEMENT DESIGN - INTERPRETATION OF RESULTS

Table 2 presents the carbon footprint of materials manufacture, transport and site activities per km of the case studies described above.

Table 2 Carbon Footprint of Road Construction Projects

Country	Project	Length	Materials (tCO_2/km)	Transport (tCO_2/km)	Construction (tCO_2/km)	Total (tCO_2/km)
UK	Trunk road	28	743	236	1,069	2,047
UAE	Option A	250	5,018	3,169	1,439	9,626
	Option B	250	4,525	2,511	1,522	8,559

Analysing the numbers in Tables 1 and 2 leads to the following observations:

- The carbon footprint per km of construction of UAE highway is substantially higher than the UK trunk road widening, indicating that new construction in general has bigger impacts than improvement works;
- Materials sourcing and manufacture in general account for the biggest portion of CO_2 from road construction, this is the case in both the UAE design options and the UK trunk road; reducing material embodied carbon thus deserves more R&D resources in a company's carbon reduction campaign;
- Carbon from site activities, i.e. electricity, fuel use, was allocated to 'construction', while in practice fuels on site may be used for local transport, thus the carbon numbers above for 'transport' may be underestimated.

CONCLUSIONS

Governments will be increasingly required to encourage advanced and performance-related road design methods and to submit regular GHG emissions accounts as part of their international commitment, in particular under the UN Climate Change Convention.

Road construction in different countries is subject to compliance with technical standards, materials availability and practice as usual.

The advantages of pavement design using end performance specifications were described within this paper and they include: wider construction options; using local, marginal, secondary and recycled materials; better quality control and durability; and improvements to road sustainability and whole life cost. The use of improved foundations (with stiffer/stabilised materials), together with the flexibility of using a wider range of HBMs, plus asphaltic and concrete materials, have helped designers to optimize the pavement construction and reduction of pavement layer thicknesses were achieved. On the other hand, there is the need for associated laboratory and end-product performance testing to assess the fundamental material engineering properties as part of the design and construction process.

The CO_2 results presented in this publication obtained by using CHANGER are compared, and investigation made to seek the causes of any differences. Several elements and their impacts are found to contribute to the variation in CO_2 per km of construction, namely but not in particular order, the technical standards (e.g. traffic, lane width), current condition (e.g. foundation, pavement surface), material option, land use change, drainage and structures (type, number, etc).

Carbon measurement of an on-going road construction is often undertaken with an absence of project data, such as materials type and quantity, transport, and paving method, etc. Data from published literature or comparable projects are normally used, and assumptions made in order to proceed with the analysis. Data validation and sensitivity check can be carried out thereafter, once the "hot spot" areas are identified. The details of proxy data and assumptions need to be documented for transparency; the aim is to allow the carbon impact of roads provision to be understood and managed on an informative basis. CHANGER can be used to check the carbon variation for alternative material options, or it can measure a project that has a multitude of technical and economic drivers. It provides a consistent process that allows road projects of different background to be measured against a consistent functional unit (i.e. per km of construction).

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