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EcoLanes: Paving the Future for Environmentally-Friendly and Economical Concrete Roads

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Abstract

With increasing oil prices the future of asphalt roads on deep foundations is becoming increasingly uncertain, due to increased costs as well as political and environmental concerns. Concrete pavement bases can reduce the foundation layers and decrease or eliminate the asphalt topping. Prior to the on-going oil crisis, concrete bases were generally more expensive to construct, and were mostly used in heavily trafficked sections and to reduce maintenance. Concrete bases are in general reinforced with steel mesh to improve their strength characteristics; however, this process is labour intensive and has health and safety problems. Premixed steel fibre reinforcement is also used to replace the mesh and provides a less laborious construction technique. Steel fibres are normally derived from virgin steel wire and are more expensive than mesh reinforcement. Recently, it has been shown that recycled steel fibres, produced from post-consumer tyres, offer an attractive low cost alternative solution. Recycled aggregates, pulverised fuel ash and low energy cements may also be employed to reduce costs and energy input. This paper presents an overview of the EcoLanes research project, which investigates the above issues and aims to develop long lasting rigid pavements for surface transport by utilising roller compaction techniques and low cost steel fibre reinforced concrete.

Keywords: RCC, concrete pavements, LLRP, recycled steel tyre-cord fibres

1. INTRODUCTION

A massive and targeted investment is currently required for the rehabilitation and extension of the European surface transport infrastructure, to provide a system able to respond to the needs of the enlarged European Union (EU), (ECTP, 2005).

The main element of surface transport infrastructure is the pavement, which can be either flexible or rigid. Flexible pavements are normally constructed with asphalt concrete, whereas Portland cement concrete is used for rigid pavements. The increasing demand to adopt innovative and durable construction practices has led to the wider use of concrete pavements, which in general have a longer working life than asphalt pavements (Embacher and Snyder, 2001).

Concrete pavements are normally reinforced with steel mesh reinforcement to improve their mechanical behaviour, reduce number of joints and minimise the foundation depth, required to achieve the necessary structural performance. Steel fibres mixed with wet concrete can be used to replace rebar reinforcement and thus reduce the labour costs associated with the placement of the reinforcement and speed-up the construction process. In general, the application of steel fibres is restrained by the high cost of the fibres, especially in countries where labour costs are relatively low. The price of industrially produced steel fibres, ranging from €800 to €15,000 per tonne, is at least 20% higher than the price of conventional steel bars and, since they are randomly mixed in a layer, larger volumes are needed to achieve equivalent structural performance. Steel fibres recycled from waste streams, such as post-consumer tyres (Figure 1), can offer an alternative solution to industrially produced steel fibres, since the value of recycled steel fibres (as scrap material) ranges from €20 to €150 per tonne (Pilakoutas *et al.*, 2004).

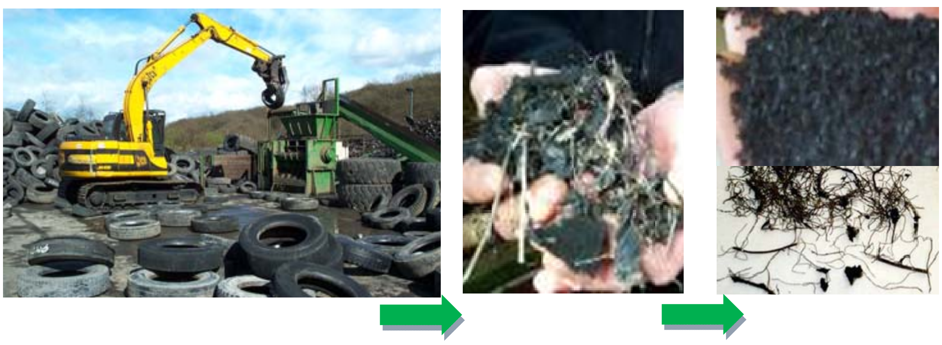

Figure 1 - Mechanical shedding of post-consumer tyres: recovery of rubber and steel

Concrete pavements are constructed using either a wet or a dry mix. The wet mix is placed and compacted with conventional concreting techniques which are laborious

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and require side formwork. Dry mixes can be placed with a modified asphalt paver and compacted by vibratory rollers (Figure 2) and, thus, provide a fast, cost-effective, and durable solution. In dry mixes, steel fibres are difficult to incorporate, but have been shown in laboratory experiments to improve the mechanical properties of dry roller-compacted concrete (Nanni, 1989).

Depending on the prevailing material and energy prices, concrete pavements could be made more cost-effective than asphalt pavements (Johnson, 2008). However, to provide a truly sustainable solution, it is necessary to reduce the energy consumption during the production of this type of pavement as well as the cost of materials. The main energy component of concrete pavements (from extraction of raw material through the placement of the pavement) is the energy used for the manufacture of cement and steel reinforcement (Zapata and Gambatese, 2004). Through the utilisation of low energy cements as well as recycled materials, such as steel tyre-cord fibres, pulverised fuel ash, and aggregates obtained from construction waste, it is possible to minimise the cost associated with the energy consumption of concrete pavements. In addition to the energy consumption, the use of low-cost recycled materials will further reduce the material cost of concrete pavements.

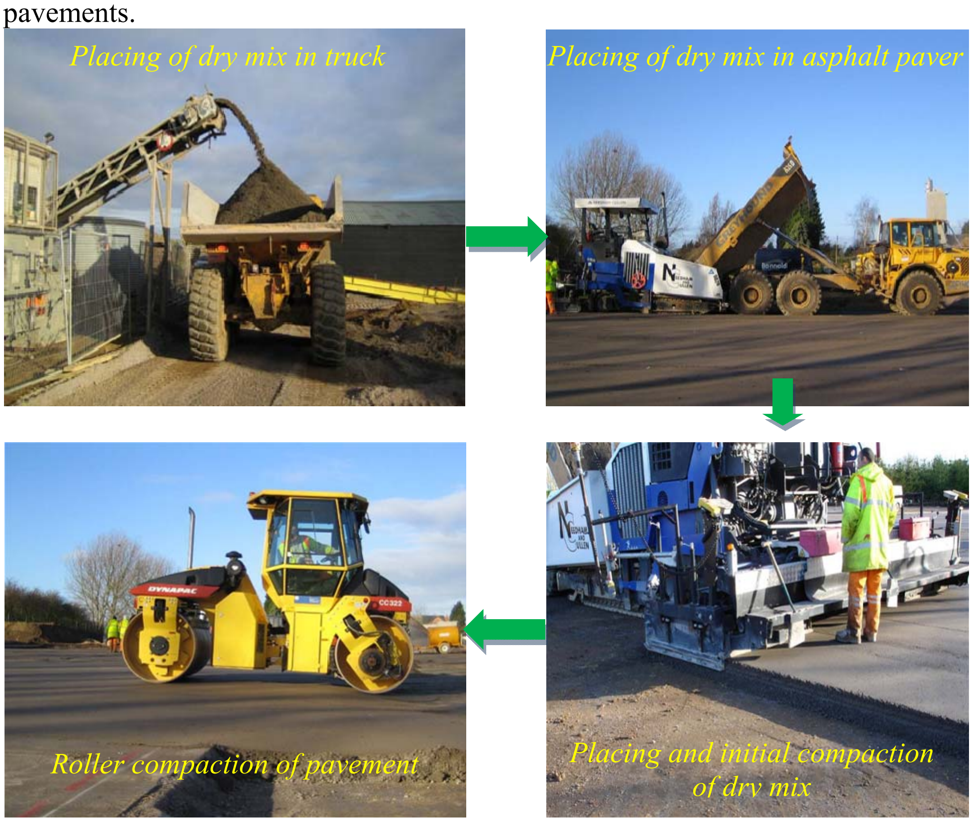

Figure 2 - Construction of roller-compacted concrete (RCC) pavements

An EC FP6 STREP project, called EcoLanes, is currently investigating the above issues and aims to develop long lasting pavement infrastructure for surface transport by using roller-compaction techniques and dry steel fibre-reinforced concrete (EcoLanes, 2008). This paper presents an overview of the EcoLanes, including its aims and objectives. In addition, the paper elaborates on the experimental work carried out to develop steel fibre reinforced roller-compacted concrete.

2. ECOLANES PROJECT OVERVIEW

EcoLanes is funded, for three years, under the priority thematic area of Sustainable Surface Transport of the 6th framework programme of the European Community. The project, which started in late 2006, draws expertise from six European countries and its consortium comprises four universities, three industrial partners, the European Tyre Recycling Association and three end-users (EcoLanes, 2008). In early 2008, Universidade Federal do Rio Grande do Sul was invited to join the EcoLanes consortium.

The main aim of this project is the development of pavement infrastructure for surface transport using roller compaction techniques (Figure 2), based on existing asphalt laying equipment, and dry concrete mixes reinforced with steel tyre-cord fibres. The benefits of the new construction concept will be manifold, such as to reduce construction costs by 10-20%, reduce construction time by at least 15%, reduce the energy consumption in road construction by 40%, minimise maintenance, use post-consumer materials in road construction and make tyre recycling more economically attractive. Through its nine work-packages (Figure 3), the project will deliver new processes, models for life-cycle assessment and costing, and design guidelines. The results of the project will be validated by constructing full-scale demonstration projects in four diverse European climates and economies (i.e. Cyprus, Romania, Turkey and United Kingdom), which will be constructed in early 2009.

To achieve its aims and objectives, the project has to overcome scientific and technological barriers in fibre processing, concrete manufacture and road design.

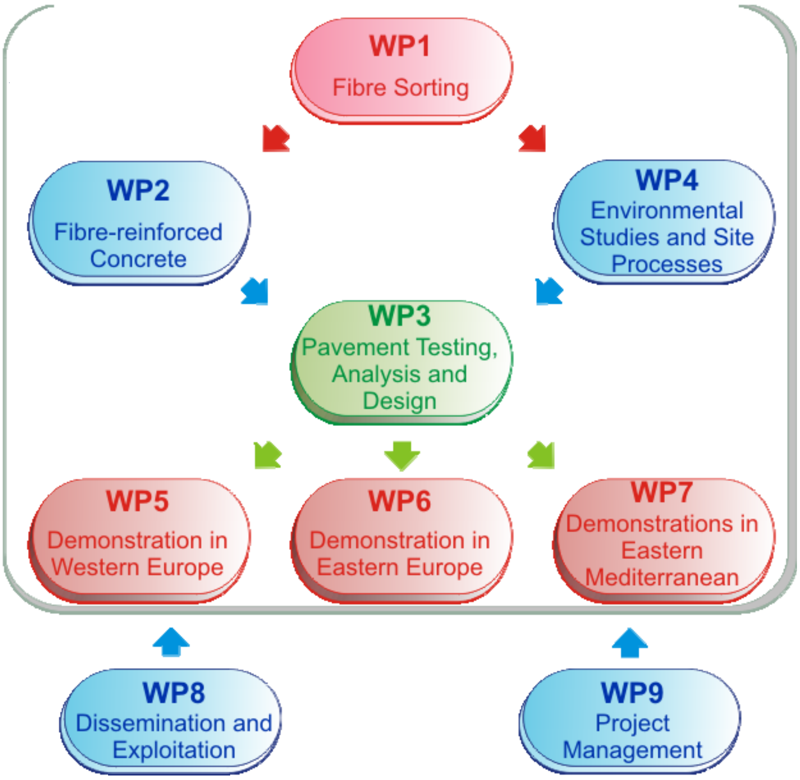

Figure 3 - EcoLanes work-package overview

2.1. Fibre Processing

Previous research has demonstrated that steel tyre-cord fibres improve the mechanical properties of concrete (Pilakoutas *et al.*, 2004). However, one of the main problems, encountered when mixing steel tyre-cord fibres in fresh concrete, is the tendency of the fibres to ball together, which spoils the concrete (Pilakoutas *et al.*, 2004). Fibre balling is mainly caused by the irregular geometry of the fibres (Figure 4). Thus, the EcoLanes project has already developed techniques and equipment that minimise the geometrical irregularities of the steel tyre-cord fibres and arrive at the optimal lengths required to best utilise the steel strength and avoid balling.

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(a)

(b)

Figure 4 – (a) Irregular steel tyre-cord fibres, produced from the shredding of post-consumer tyres (b) Fibre balling in wet-mix concrete

2.2. Concrete Engineering

Despite the improved mechanical properties of steel fibre-reinforced roller-compacted concrete (SFR-RCC), the addition of steel fibres can lead to compaction problems and, thus, affect the concrete density. Damage may also be caused to the steel fibres during the compaction process. These problems are being tackled by EcoLanes though extensive laboratory experiments (section 3) prior to the full scale trials of the demonstration projects.

In addition, SFR-RCC has not been used extensively, up to now, due to the difficulties in incorporating the fibres in the dry mix. To eliminate this technological barrier, the EcoLanes consortium is examining various industrial processes and equipment which could be used to successfully disperse steel fibres in dry mixes, and maximise the amount of fibre content added to the mix without attaining balling. In June and September 2008, pre-demonstration trials were carried out in the United Kingdom and Romania, respectively, to assess the suitability of pan mixers for producing SFR-RCC. The results of the trial (Figures 5

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and 6) were satisfactory as the fibres were evenly distributed in the dry mix with minimal fibre balling.

Figure 5 – SFR-RCC produced in an industrial pan mixer

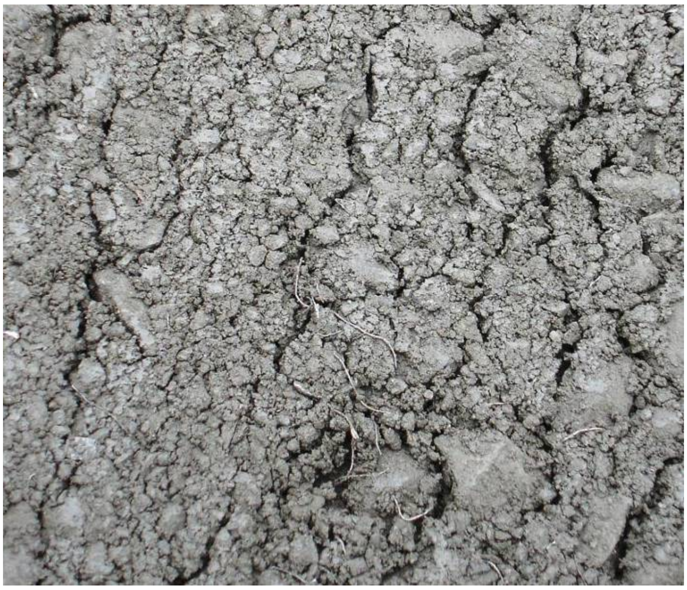
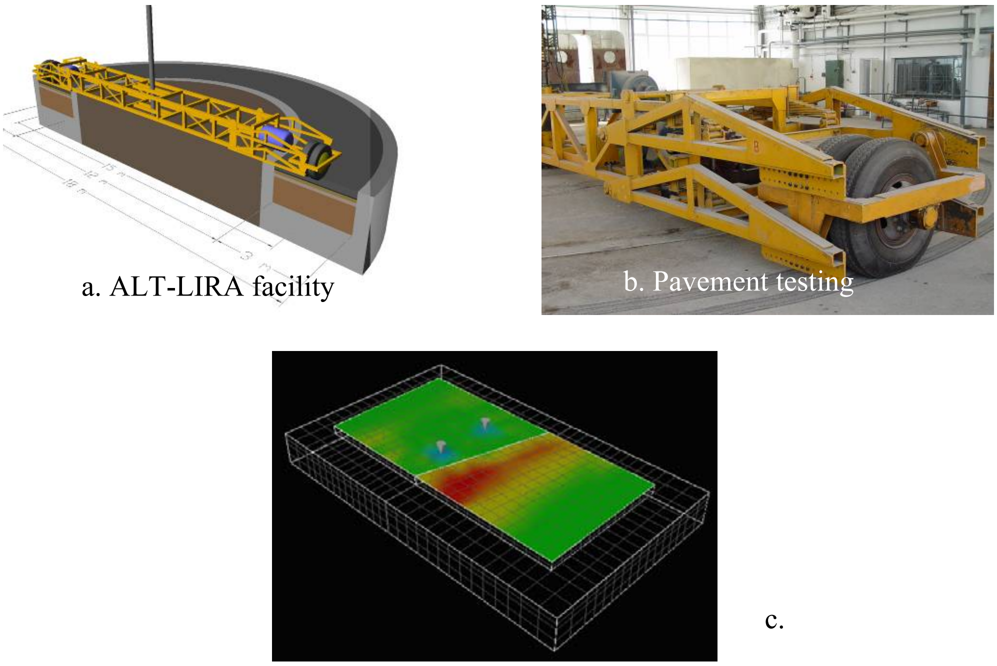


Figure 6 – Surface of SFR-RCC pavement following paver compaction

2.3. Road Design

The economic and sustainable design of concrete pavement is a complex calculation requiring input ranging from the material (physical, mechanical, chemical) characteristics and cost, energy inputs, cost of labour, equipment and fuel, to advanced numerical techniques. All these parameters will be determined through the development of the concept of the long lasting rigid pavement (LLRP), which will also consider the results of life cycle assessment and costing. The LLRP concept is currently being technically validated on a circular accelerated testing facility (where sections of selected SFR-RCC mixes will be subjected to 1.5 million load cycles), and numerical analyses and parametric studies will be carried out to develop design models for LLRPs (Andrei *et al.*, 2007; Vlad *et al.*, 2008; EcoLanes, 2008).



a. ALT-LIRA facility

b. Pavement testing

c.

Figure 7 - Technical validation of concept of long lasting rigid pavements

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3. STEEL FIBRE-REINFORCED ROLLER-COMPACTED CONCRETE

The main aim of EcoLanes work package 2 (WP2) is the development of SFR-RCC mixes, which have reduced energy requirements and use recycled materials, such as recycled aggregates and steel tyre-cord fibres, cement replacements (e.g. pulverised fuel ash), and low energy cements. To achieve this aim, WP-2 comprises the following five tasks.

- Reviewing use and design of steel fibres in concrete pavements to determine the ideal characteristics of steel fibres to be used in the SFR-RCC. For comparison purposes, industrially produced steel fibres are considered in addition to the steel tyre-cord fibres.
- Initial optimisation of the SFR-RCC mixes by considering various factors, such as cement type and content, aggregate type and content as well as fibre type and content. The main objective of this task is to determine the basic mechanical characteristics of each mix, such as compressive strength and elastic modulus.
- Flexural characterisation of the optimised SFR-RCC mixes by performing bending tests of prisms. The main objective of these tests is to asses whether the post-cracking resistance of SFR-RCC.
- Performing corrosion and chloride ingression tests as well as freeze-thaw tests with combined salt-stress. These tests started in early 2008 and their main aim is to assess the resistance of the developed SFR-RCC mixes to the main aggressive agents that surface transport infrastructure is normally subjected to.
- Development of models for the mechanical behaviour of the proposed SFR-RCC mixes by carrying out numerical analysis, including finite element and cross-sectional analyses. These models would then be used for the development of the LLRP concept and for the design of the four demonstration pavements.

3.1 Bending Behaviour of SFR-RCC

Bending tests were performed on rectangular prisms to evaluate the flexural strength characteristics (toughness) of the SFR-RCC mixes developed by WP2. Two types of recycled fibres, with different length distributions, were considered. Type A had a length range between 5-20 mm, while Type B ranged between 15-30 mm. Both types had an average diameter of 0.23 mm and a tensile strength of around 2000 MPa. In addition to the recycled steel fibres, two different types of industrially produced steel fibres were also considered: HE1/50 and BE1/50. The former is a loose cold drawn wire fibre with hooked ends, while the latter is a straight fibre with button ends (Figure 8). Both fibre types were 50 mm long, 1.0 mm in diameter and had a tensile strength of around 1000 MPa.

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(a) (b

Figure 8 - Industrially produced fibres: (a) HE1/50 and (b) BE1/50

3.2 SFR-RCC Specimen Preparation

The SFR-RCC prisms were 150 mm deep, 150 mm wide and 550 mm long. Steel-plate moulds were used to eliminate the deformation of the moulds, caused by the severe external compaction. The specimens were cast in three layers and compacted by a suitable vibratory kango hammer. Following the recommendations of the RILEM bending test (RILEM, 2002), a day after casting, the specimens were demoulded and then placed in the mist room (+20°C and RH>95) until the day of testing. On the day of testing, a notch (25 mm high and 5 mm thick) was sawn at mid-span, into the tensile face of each rectangular prism (at a 90 degrees angle to the RCC layers), using rotating diamond blades. The purpose of the notch was to act as a crack inducer.

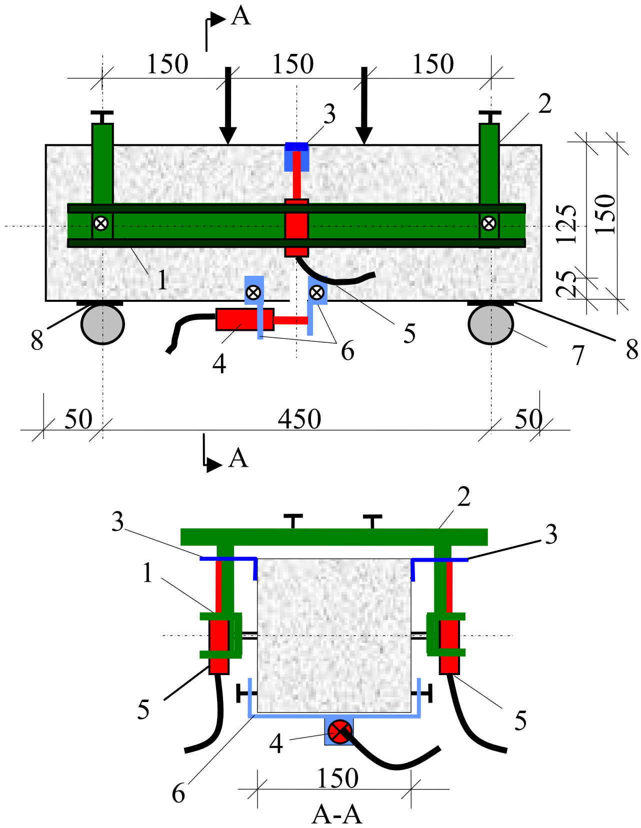
3.3 Testing Procedure

The testing of the notched prisms was carried out by following the recommendation of the RILEM bending test. It is noted that a four-point load arrangement was used instead of three-point load. The use of four-point load arrangement creates a region of constant moment and, hence, minimises the overestimation of bending resistance, caused at the point of load application by the load-spreading effect. The two supports and the device for imposing deformation consists of steel rollers with a diameter of 30 mm. Two rollers (one at the support and one at the device imposing the deformation) are capable of rotating freely around their axis and the longitudinal axis of the test specimen. All rollers are placed on steel plates (5 mm thick) to avoid local crushing of concrete and extraneous deformations.

Results from bending tests on concrete prisms are prone to significant experimental errors (due to spurious support displacements, machine stiffness and load rate) and, hence, extra care is required to obtain accurate deflection measurements (Copalaratnam and Gettu, 1995). To avoid these errors and the effect of torsion on the deflection measurements, a yoke was used as specified by the Japan Society of Civil Engineers (1994).

Average mid-span beam deflections were measured on both sides of the prisms using two transducers fixed to the yoke (LVDT5) and, hence, any torsional effects were cancelled out. One transducer (LVDT4) was mounted across the notch mouth to monitor the crack mouth opening displacement (CMOD), as illustrated in Figure

9. The SFR-RCC specimens were tested in a 100 kN servo-hydraulic machine under crack-mouth-opening-displacement control (CMOD). The machine was operated in such a manner that the CMOD was increased at a constant rate of 60 µm/min for CMOD ranging from 0-0.1 mm and 0.2 mm/min for CMOD from 0.1 mm until the end of the test.



1- Steel bar; 2- clamps with pins; 3- steel plate (glued to the prism); 4 - LVDT4; 5 – LVDT5; 6- clamps for LVDT; 7- supports, 8 - steel plates

Figure 9 - Set-up used for the bending test for RCC prisms

3.4 Bending Test Results

Figure 10 presents the bottom face of a cracked (in flexure) SFR-RCC specimen focusing on the fibre pull-out along the induced crack. The effect of fibre volume on the flexural behaviour of these specimens is shown in Figures 11 and 12. Figure 11 shows the flexural behaviour of specimens reinforced with industrial steel fibres; while, Figure 12 shows the flexural behaviour of specimens reinforced with

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steel tyre-cord fibres. It is apparent that an increase in the fibre volume, increases both the flexural strength and the residual strength following the initiation of cracking. The same trend was observed for all the different fibre types considered, with the industrial fibres being more effective.

Figure 10 - Fibre pull-out of a cracked SFR-RCC specimen

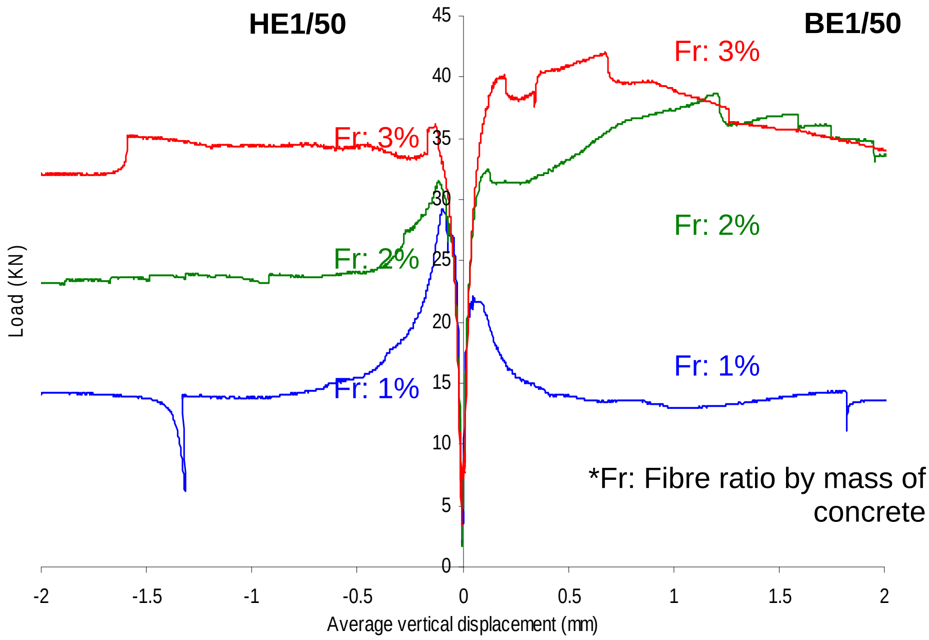

Figure 11 - Flexural behaviour of SFR-RCC utilising industrial fibres (3-day test)

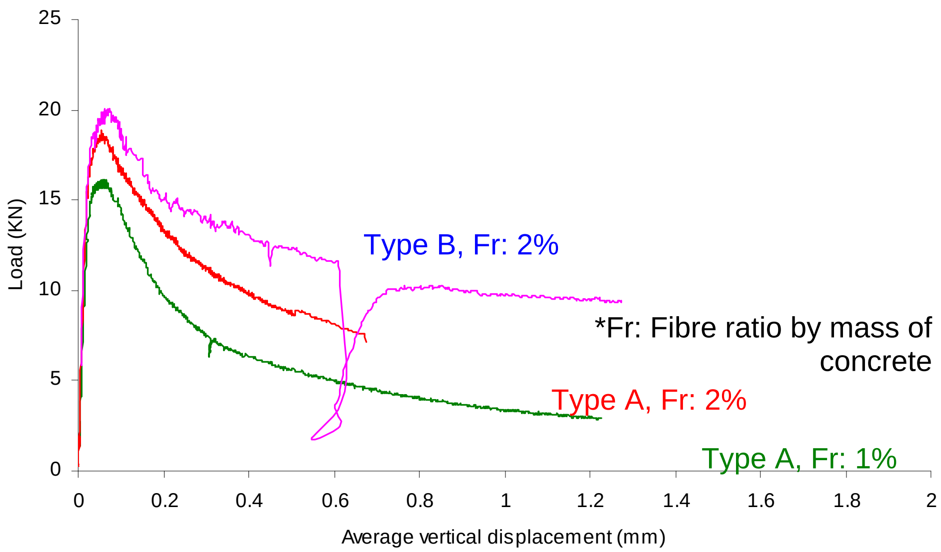

Figure 12 - Flexural behaviour of SFR-RCC utilising recycled fibres (3-day test)

The effect of fibre shape on the toughness can also be observed in Figures 11 and 12. Specimens reinforced with industrial steel fibres have higher modulus of rupture and present better post-cracking behaviour. This is largely attributed to the beneficial effect that the deformed ends have on mechanical bond, increasing SFR-RCC ductility. Flexural failure of the specimens occurred mainly due to fibre pullout. It is noted that, in specimens reinforced with the BE1/50 fibres, up to 50% of the fibres experienced fracture at their ends prior to pull out; increasing the energy absorption capacity of their specimens. BE1/50 fibre fracture is an indication of the high involvement of this type of fibres, demonstrated by the 'strain hardening behaviour', at fibre ratios higher than 2% by weight.

Figure 13 illustrates the positive effect of increased fibre length on the flexural residual load. Specimens with 50 mm long fibres exhibited an extended and more stable post-peak load- vertical displacement response, contrary to the limited vertical displacement obtained by the specimens with 5-20 mm and 15-30 mm long fibres (at low fibre ratios). A comparison of the two recycled fibre types (Fibre Type A and B) further reinforces this observation as the longer Type B fibres show a better post-cracking behaviour.

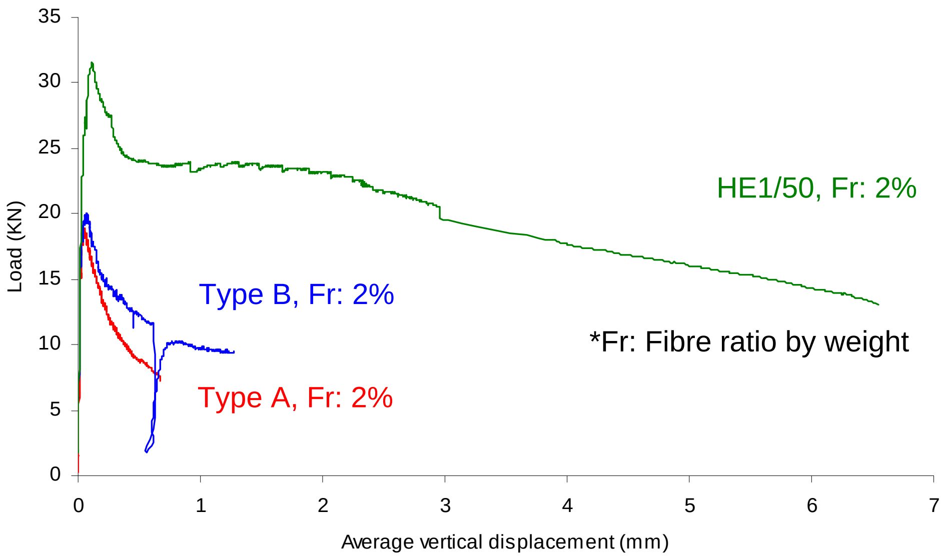

Figure 13 - Effect of fibre length on the flexural toughness (SFR-RCC) (3-day test)

4. CONCLUSIONS

Surface transport pavements are currently constructed using asphalt concrete, whilst Portland cement concrete is mainly used for heavy trafficked pavements. Often concrete pavements are reinforced with steel reinforcement to improve the concrete's mechanical properties and reduce the pavement's depth.

Despite the increasing prices of crude oil, the material cost of concrete pavements can still be higher than that of asphalt pavements and, hence, in order to provide a truly economical and sustainable solution for concrete pavements, it is necessary to utilise low-cost materials and to evaluate the energy cost as well as the cost of maintenance.

Research currently performed as part of the EU FP6 EcoLanes project aims to develop low-cost steel fibre reinforced concrete pavements by utilising roller-compaction techniques and recycled materials, such as steel tyre-cord fibres, cement replacements and recycled aggregates. It is expected that this construction concept will reduce the construction cost and time as well as the energy consumption in road construction.

Preliminary results obtained from bending tests of SFR-RCC prisms, carried out as part of the EcoLanes activities, have highlighted the importance of fibre geometry. The fibres examined from industrial sources resulted in better overall behaviour compared to the fibres recovered from post consumer tyres, at equivalent fibre ratios. However, if these fibres are mixed at higher fibre ratios they could be used as a viable alternative to the industrial fibres.

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