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Steel fibre reinforced roller compacted concrete Roads

Angelakopoulos H., Neocleous K. and Pilakoutas K.
Department of Civil & Structural Engineering
The University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom

Summary

This paper describes the use of steel fibres in Roller Compacted Concrete (RCC) for pavement applications. This work is part of the EU funded project Ecolanes, which aims to develop long lasting rigid pavements. It begins by discussing the benefits associated with rigid pavements with a special reference to fibre reinforced concrete and RCC. The objective of the specific part of the presented work is to investigate the effect of adding fibres in RCC from a structural standpoint, and to discuss the improvement in strength and toughness characteristics, and comment on the effect that different fibre types may have as reinforcement. The importance of fibre geometry on the flexural behaviour of steel fibre reinforced RCC (SFR-RCC) is demonstrated. RCC reinforced with fibres obtained from industrial sources and fibres obtained from the bead wire of recycled tyres, resulted in better flexural behaviour, compared to RCC reinforced with tyre cord fibres recovered from recycled tyres, at equivalent fibre ratios. However, the recycled tyre cord fibres could be a viable alternative if used at higher fibre volumes.

Keywords: Pavement, Roller Compacted concrete, Fibre reinforced concrete, Recycled materials.

1 INTRODUCTION

A significant and targeted investment (approximately €600bn by 2010) is currently required for the rehabilitation and extension of the European surface transport infrastructure, to provide an adequate system to respond to the needs of the enlarged European Union, for the benefit of the single market and economic and socio-economic integration [1,2]. The core element of surface transport infrastructure is the pavement, which can be either flexible or rigid. Flexible pavements are normally constructed with asphalt, whereas Portland Cement Concrete (PCC) is the main material used in rigid pavements, which may be reinforced either with conventional steel mesh or steel fibres.

With rapidly escalating oil prices the future of flexible pavements, which require deep foundations and deep asphalt layers, is becoming progressively more uncertain due to increasing costs as well as political and environmental concerns.

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Although conventional concrete pavements can significantly reduce the foundation layers, decrease or eliminate the asphalt topping and reduce maintenance requirements, they are currently associated with higher costs and increased construction complexity due to the use of reinforcing mesh. Steel fibre reinforced concrete (SFRC) could eliminate the use of mesh reinforcement and allow the use of the roller compacted method to lay the concrete, bringing significant savings in both time and money in pavement construction. Nevertheless, in order to provide an economical and sustainable solution for concrete pavements, it is necessary to utilise materials coming from various waste streams and to carefully evaluate their energy requirements as well as the cost of maintenance.

In the next sections follows a discussion on the benefits associated with concrete pavements with special reference to steel fibre reinforced concrete (SFRC) and RCC. After that follows a detailed description of the bending tests performed, including details of the different types of fibre reinforcement involved. Finally a discussion on the main conclusions drawn from the bending test results is presented.

2 RIGID, FLEXIBLE OR A HYBRID PAVEMENT?

Rigid pavements have a longer working life (approximately 40 years) outlasting flexible materials by approximately 20 years. In addition rigid pavements require less maintenance, whilst when repairs are necessary they are typically smaller in scope than for flexible pavements [3]. Furthermore, in presence of heavy vehicles, flexible pavements experience greater deflections compared to rigid pavements, causing 11% higher vehicle fuel consumption [4]. Additionally, the effect of seasonal changes in the smoothness of rigid pavements is significantly lower, which also contributes to higher fuel efficiency. Rigid pavements due to their stiffness can withstand even the heaviest traffic loads without suffering distress (e.g. rutting and shoving) common with flexible pavements. Rigid pavements continuously gain strength over time, and quite often exceed their design life expectancy as well as the design traffic loads. Moreover, restoration techniques can extend the life of rigid pavements up to nine times their original design life [3,5].

A key feature of rigid pavements is that they can be reinforced and minimise cracks which, in combination with their high material stiffness, reduces the required pavement thickness to carry the expected traffic loads, and in many cases a solution is achieved with single layer construction.

In terms of cost, the price of PCC has remained relatively stable over recent years, while hot mix asphalt prices have risen significantly. This trend is anticipated to continue. In particular, the Producer Price Index (PPI) for liquid asphalt at the refinery (as tracked by the U.S. Bureau of Labour Statistics) had risen by February 2007 nearly 37% over the preceding 12 months, compared to nearly 6% for cement. The PPI for asphalt paving mixes had increased just over 27% in the 12 months ending December 2006, while ready mixed concrete had risen nearly 10% [6].

The main limitations associated with rigid pavements are poor surface skid resistance, noise generated from traffic and their relatively high current cost [7]. However, a combination of a rigid pavement with an ultra thin asphalt overlay can enhance the ride quality of the pavement, without the problems traditionally associated with deep asphalt pavements, and this is an attractive option. Despite the increasing prices of asphalt, the material cost of rigid pavements may still be higher than that of asphalt pavements and, hence, at this moment in time an economical and sustainable solution for rigid pavements, could be derived through the utilisation of low-cost materials and by making use of processes (eg. roller compaction) that are fast and economical.

2.1. Roller compacted concrete

Figure 1, depicts a typical construction scene of pavement construction that is used in nearly any street of every city. A careful inspection of Figure 1, however, confirms that the material in use is grey concrete, not asphalt, but it is not conventional concrete either. It is a material called Roller Compacted Concrete (RCC), named after the technique used to compact it.

RCC is a construction material made from the combination of aggregates, water and binder. Although the same ingredients as for conventional concrete are used, these are mixed at different proportions resulting in a material with improved properties and behaviour. The ingredients are mixed in a central batching plant or in a Pugmill mobile mixer, targeting the production of a heterogeneous mass which has consistency representative of zero slump concrete [8]. This is needed so that the concrete can support the weight of vibratory rollers (approx. 10tons) as soon as it is layed in a similar way to asphalt. It can be said that asphalt is a form of concrete with bituminous materials replacing cements.

RCC aims to provide the relatively high strength and durability of concrete, at the economy and speed of construction traditionally associated with asphalt. This very attractive material could further benefit from utilisation of fibre reinforcement.

Figure 1: Paving operation and compaction of the pavement by heavy vibratory rollers

2.2. Steel fibre reinforced concrete

Fibres are added in concrete to minimise cracks, to enhance toughness and improve surface characteristics. In particular, the addition of steel fibres can offer high first crack flexural strength, improved shear strength, high flexural fatigue endurance limit, good impact resistance, enhanced freeze-thaw durability, ability to carry load after the formation of cracks and high spall resistance. SFRC can also benefit from thickness reduction without experiencing the problems of curling and warping as may be seen in high cement content, thin slabs [9].

From the construction perspective, the use of steel fibres, can eliminate the need for conventional re-bars and, hence, lead to cost savings and increased speed in construction [10,11].

3. BENDING BEHAVIOUR OF STEEL FIBRE REINFORCED RCC

Bending tests were performed on rectangular prisms to evaluate the flexural strength characteristics (toughness) of SFR-RCC. The next sub-sections present a description of the steel fibre reinforcement investigated, the specimen preparation technique used, the testing procedure followed and the results obtained from the bending tests performed on rectangular SFR-RCC prisms.

3.1. Steel fibres extracted from post consumer tyres

Steel tyre-cord fibres, produced from the mechanical treatment (e.g. shredding and granulation) of post-consumer tyres, have high variability in length and diameter and in most of the cases they contain significant amounts of rubber particles on their surface.

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 [12]. To avoid balling and to optimise the use of such fibres in concrete, the fibres need further treatment to remove the rubber particles and minimise the geometrical irregularities [13].

Three types of recycled tyre cord fibres, with different length distributions, were considered in this investigation. RTC1-11 fibre type had a length range between 1-11mm, while RTC1-17 ranged between 1-17mm and RTC3-40 between 3-40mm. The RTC fibre types had an average diameter of 0.23mm and a tensile strength of around 2000MPa. In addition to the RTC fibres a fibre made from the tyre bead wire used, namely I2H2x1/80. The I2H1x2/80 is a fibre with hooked ends, a rectangular cross section of 1x2mm and an average length of 80mm with a tensile strength of around 2000MPa.

3.2. Industrially produced steel fibres

The four different types of industrially produced steel fibres used in this study were I2H1/50, I2H.75/50, I2H1/60 and I2C1/54. I2H, is a loose cold drawn wire fibre with hooked ends, Figure 2a. These fibres are filaments of wire, deformed and cut to lengths, for reinforcement of concrete. The geometrical properties of the fibre are 50mm and 60mm in length, and 1mm in diameter, with a tensile strength of around 1100MPa. I2C1/54 fibres have the same properties as I2H type fibres with the only difference being their cone-ends, Figure 2b.

(a) (b)

Figure 2: Industrially produced fibres: (a) I2H; (b) I2C1/54

3.3. SFRRCC specimen preparation

The SFRRCC prisms were 150mm deep, 150mm wide and 550mm 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.

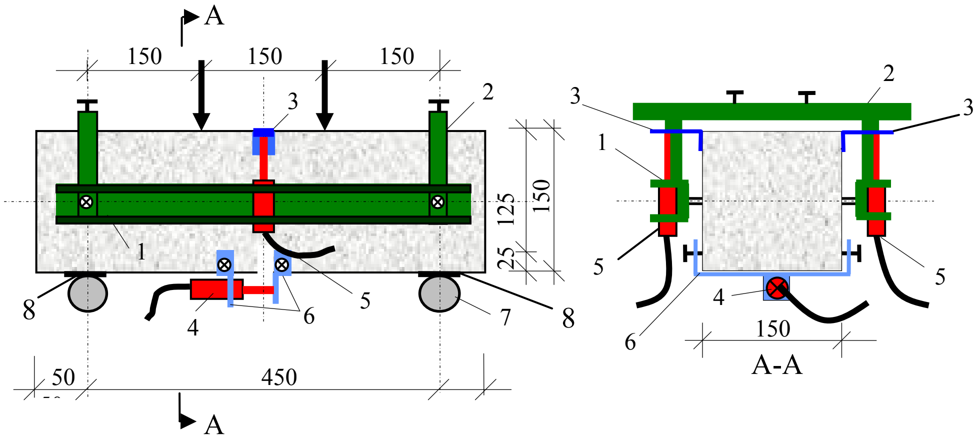
Following the recommendations of the RILEM bending test [16], a day after casting, the specimens were demoulded and then placed in the mist room ($+20°C$ and $RH \geq 95$) until the day of testing. On the day of testing, a notch (25mm high and 5mm thick) was sawn at mid-span, into the tensile face of 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 [13].

3.4. Testing procedure

Testing of the notched prisms was carried out by following the recommendation of the RILEM bending test [14]. 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 [15]. The two supports and the device for imposing deformation consists of steel rollers with a diameter of 30mm. 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 [14]. All rollers are placed on steel plates (5mm 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 [16]. 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 [17].

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 3.



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 3: Set-up used for the bending test for RCC prisms

The SFRRCC 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 $60\,\mu m/\min$ for CMOD ranging from $0-0.1mm$ and $0.2\,mm/\min$ for CMOD from $0.1mm$ until the end of the test [14].

3.5. BENDING TEST RESULTS

Overall RCC reinforced with any type of steel fibres presented improved performance compared to plain RCC, with some fibres being more effective than others depending on their specific characteristics. The effect of adding fibres on the flexural behaviour of RCC is illustrated in Figures 4, 5 & 6. Figure 4 shows the flexural behaviour of RCC specimens reinforced with four different types of industrial steel fibres; while, Figure 5 shows the flexural behaviour of specimens reinforced with steel tyre-cord and hooked-end bead wire fibres. In Figure 6, the bending behaviour of RCC with high fibre volumes of RTC fibres is presented.

At equivalent fibre ratios specimens with relatively long steel fibres (i.e. length > 50mm) exhibited an extended and more stable post-peak load-vertical displacement response, contrary to the limited vertical displacement obtained by the specimens with 1-11mm and 3-40mm long fibres. A comparison between the two short recycled fibre types (RTC1-11 and RTC3-40) further reinforces this observation as the longer RTC3-40 fibres show an improved post-cracking behaviour.

The effect of fibre shape on the toughness can also be observed in Figures 4, 5 & 6. Specimens reinforced with fibres having deformed ends presented higher modulus of rupture and better post-cracking behaviour at equivalent fibre ratios. This is largely attributed to the beneficial effect that the deformed ends have on mechanical bond, dramatically increasing SFRRCC ductility.

Flexural failure of the specimens occurred mainly due to fibre pullout. It is noted that, in specimens reinforced with the I2C1/54 fibres, up to 50% of the fibres experienced fracture at their ends prior to pull out; increasing the energy absorption capacity of their specimens. I2C1/54 fibre fracture is an indication of the high involvement of this type of fibres, demonstrated by hardening behaviour, at fibre ratios higher than 2% by mass (50kg/m^3).

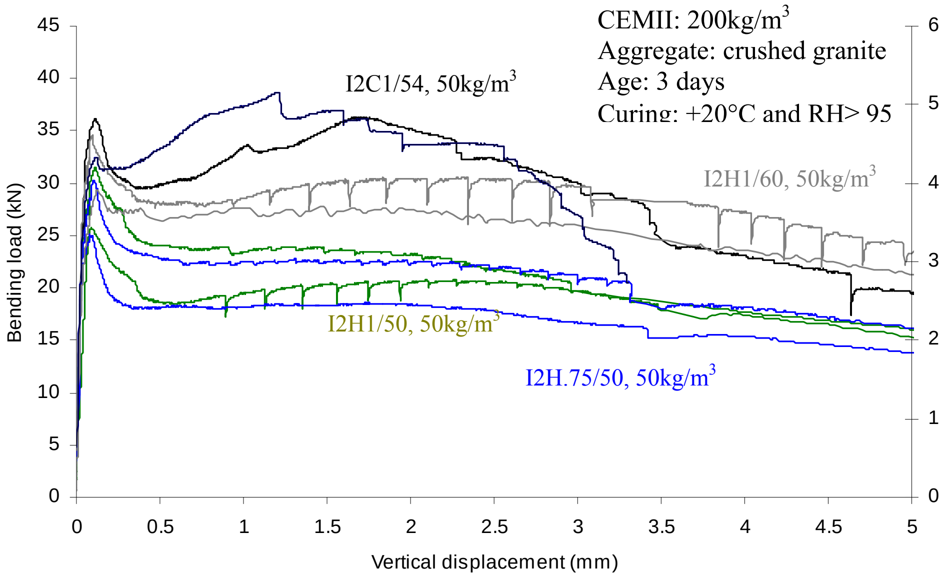


Figure 4: Flexural behaviour of SFR-RCC utilising industrial fibres (3-day test)

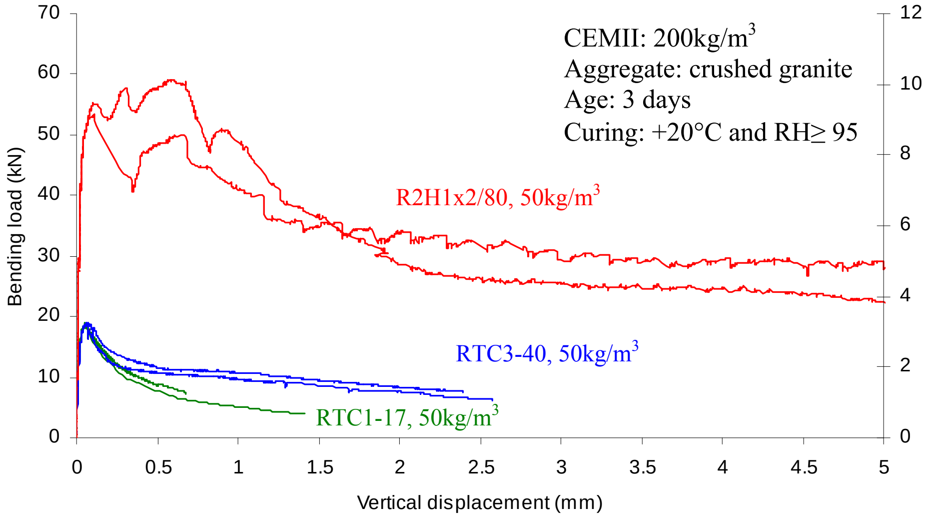


Figure 5: Flexural behaviour of SFR-RCC utilising recycled fibres (3-day test)

From Figure 6, it is apparent that by increasing the RTC fibre content by approximately three times the flexural strength could be doubled and the residual strength following the initiation of cracking, significantly improved. The flexural peak strength achieved by specimens reinforced with RTC fibres at fibre contents of 150kg/m^3 were superior to the flexural strengths achieved with 50kg/m^3 of industrial fibres and comparable to the strengths achieved with R2H1x2/80 fibres. The efficiency issue with the relatively short RTC fibres could be compensated by their low price. The price of industrially produced steel fibres is ranging from €700 to €15,000 per tonne (at least 20% higher than the price of conventional steel bars), while the RTC price is between €50 to €150 per tonne.

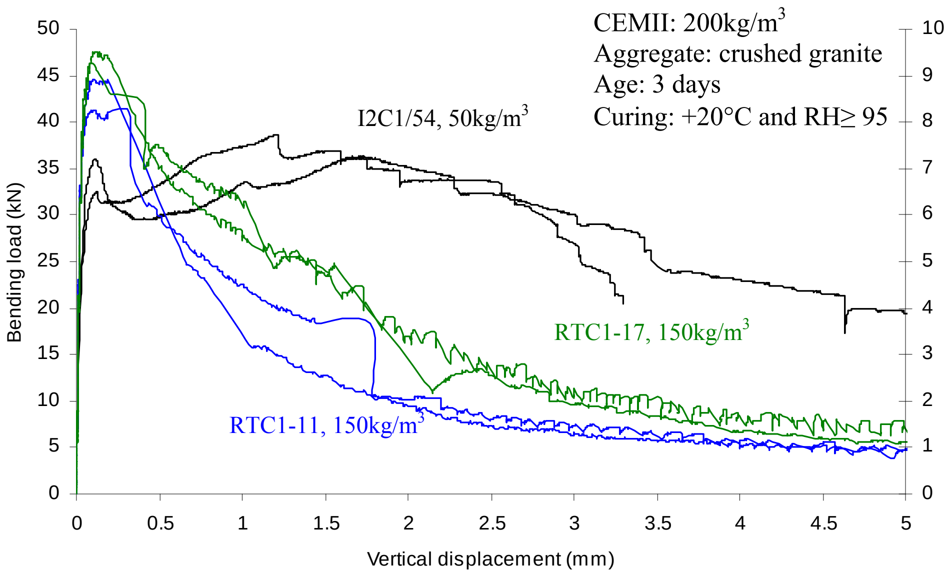


Figure 6: Flexural behaviour of SFRRCC utilising high fibre volumes of RTC fibres (3-day test)

4. CONCLUSIONS & FUTURE WORK

The increasing demand to adopt innovative, sustainable as well as cost-effective construction practices leads to the wider use of concrete pavements. RCC offers the high strength and durability of concrete, at the economy and speed of construction traditionally associated with asphalt. The utilisation of fibre reinforcement brings significant benefits in construction processes and improves significantly ductility characteristics and the modulus of rupture of RCC which is the main property of interest currently in pavement design.

The importance of fibre geometry on the flexural behaviour of RCC has been demonstrated, with length and shape having significant effect. The fibres examined from industrial sources and the recycled bead wire fibres resulted in better overall behaviour compared to the short RTC fibres, at equivalent fibre ratios.

Although, the short tyre cord fibres presented an inferior behaviour compared to the industrial fibres, if they are mixed at higher fibre ratios (approximately 3 times higher) they could be used as a viable alternative to the expensive industrial fibres.

Further work needs to be concentrated on examining several different RTC fibre length distributions to assess their performance in RCC. This is a necessary step on the implementation of these fibres as different tyre shredding plants use different tyre shredding processes resulting to variable fibre length distributions.

5. ACKNOWLEDGMENTS

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