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Fibrous roller-compacted concrete with recycled materials – feasibility study

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This paper presents fundamental work done to enable fibre reinforcement of roller-compacted concrete (RCC). Procedures for mixing and casting two types of steel fibres in RCC were developed. Fresh properties, uniaxial compressive and bending behaviour were examined in a pilot study dealing with cement content, fibre type and dosage. It was found that different fibre types and dosages require different moisture contents. It is concluded that low cement content (less than 300 kg/m^3) steel-fibre-reinforced roller-compacted concrete (SFR-RCC) mixes do not have sufficient paste and are prone to fibre agglomeration, hence SFR-RCC mixes richer in paste and at optimum moisture content are recommended. Mixes with cement content of 300 kg/m^3 coped better with fibre reinforcement. Despite causing some loss in compressive strength, fibres help enhance the flexural performance and even SFR-RCC mixes with recycled masonry and concrete aggregates performed equally well as natural aggregate mixes. A full-scale trial has been conducted to confirm the findings. This paper is followed by a companion paper dealing with a comprehensive parametric study leading to the development of σ–ε models for SFR-RCC.

Notation

f_c	uniaxial compressive strength (MPa)
m_f	mass of fibres (kg)
m_{RCC}	mass of RCC matrix (kg)
$m_{SFR\text{-}RCC}$	mass of composite (kg)
$R_{0 \cdot 5}$	ratio of average load resisted when the beam deflects to 0·5 mm to the load at first crack
υ_v	void ratio
ρ	density (kg/m^3)
ρ_f	density of fibres (kg/m^3)
ρ_{RCC}	density of RCC matrix (kg/m^3)
$\rho_{SFR\text{-}RCC}$	density of composite (kg/m^3)

Introduction

Roller-compacted concrete (RCC) is a mixture of aggregates, cementitious materials and water, blended into a homogeneous mass that has a consistency similar to damp gravel or zero-slump concrete (ACI, 1995). It is normally used in mass concrete applications (e.g. dams) and for rapid construction (e.g. road pavements). RCC is attractive as it provides high strength and durability at the speed of construction conventionally associated with asphalt (ACI, 1996).

Currently, only high-quality natural aggregates (NA) are used for RCC applications and such aggregates are often transported to site from remote locations, decreasing the environmental credentials of RCC. Using lower-grade aggregates or recycled aggregates (RA) is not only a more cost-effective solution but it can also reduce the environmental impact of RCC. No studies on the use of RA in RCC have been reported, mainly because of issues such as high porosity, variability, low aggregate resistance to roller compaction and consequently low flexural strength. In slabs on grade, the main issues are low flexural strength and shrinkage cracking, which could be addressed if RCC were reinforced with steel fibres.

Due to practical and economic reasons, RCC is currently used unreinforced. As with conventional concrete, reinforcing RCC could reduce slab thickness and provide toughness and crack control. Few trials have been attempted on reinforcing RCC using relatively low dosages of rigid discrete steel fibres. Limited work is reported on the properties of steel-fibre-reinforced roller-compacted concrete (SFR-RCC) (Houssien, 1992; Makoto *et al.*, 2001; Nanni, 1989) and more research is needed to better understand SFR-RCC and identify fibre dosage limits.

In the European Union (EU) alone, the construction industry uses about 150 000 t of new steel fibres as reinforcement in concrete each year. About twice this amount of steel wire is extracted each year as a by-product from the mechanical shredding of post-consumer car and truck tyres. Most of this tyre wire is too contaminated with rubber to be recycled by steel mills and requires further cleaning and bailing before it can be re-melted. European legislation (EC, 1999) prevents tyre components from being landfilled and thus tyre steel is widely available in Europe (and throughout the world). Research on reused tyre steel fibres (RTSF) has been undertaken since 2000 at the University of Sheffield and patents have been granted for its use in concrete (Pilakoutas and Waldron, 2000). RTSF are flexible fibres that may be easier to introduce in a dry concrete mix and are thus promising candidates for reinforcing RCC and recycled aggregate RCC.

Fundamental work is therefore required to investigate the effects of various recycled materials, such as RA and different types of fibres, including reused fibres from tyres at various dosages, on the mechanical properties of SFR-RCC. This paper presents an initial experimental feasibility study on the use of RTSF and RA in RCC, which subsequently led to the first full-scale demonstration project. The paper deals initially with materials and compaction procedures and then presents and discusses results from compressive and flexural tests.

This work was undertaken as part of the EU FP6 EcoLanes project, which is aimed at developing long-lasting rigid pavement infrastructure by using 'low-energy' SFR-RCC and existing asphalt paving equipment.

Materials and experimental procedure

Steel fibres

Reused tyre wire fibres

Steel used in tyres is of high quality and strength, exceeding 2000 MPa. It is used in wire bundles in tyre beads (0·5–2·0 mm) and in cord form (strand diameter 0·7–1·0 mm) in the belts and inner liners. The bead wire is sometimes extracted before tyre shredding, while the cord wire is invariably broken down into individual steel fibres when the shreds are granulated. These individual steel fibres are of diameter 0·1–0·3 mm. Until recently, due to contamination and fineness (Figure 1(a)), much of the recovered steel was sent to landfill as, being light, it can rise with air and cause problems in steel furnace filters. Tyre steel can be re-melted for steel production and eventually turned into wire, but this is two orders of magnitude more energy intensive than reusing the fibres directly in concrete after cleaning and sorting.

A few hundred tonnes of clean, sorted and classified RTSF (Figure 1(b)) were produced by the EcoLanes project, which, at its closing stages, undertook four major demonstration projects in the UK, Turkey, Romania and Cyprus. Currently, large-scale industrial processes are being developed by the EU Eco-innovation project Twincletoes (Twincletoes, 2015) and the first commercial applications in slabs on grade (with conventional concrete) were completed in 2013.

For the purposes of this study, three types of clean and sorted reused tyre wire fibres were used: RTSF1-10, RTSF1-20 and RTSF5-40. To identify the statistical fibre length distribution an 80% range was adopted; that is, 10% of the fibres were below the specified length and 10% of the fibres above the specified length. Hence for RTSF5-40, 10% of fibres were below 5 mm length and 10% were above 40 mm.

Manufactured steel fibres

For comparison purposes, three common types of manufactured fibres were used in this study: cone-end (M2C1/54), hooked-end

(a) (b)

Figure 1. Tyre wire: (a) unsorted and contaminated material directly from the shredding of post-consumer tyres; (b) clean and sorted RTSF

(M2H1/50) and undulated (MUND1/50), all with the same nominal tensile strength of 1100 MPa.

Aggregates

Natural aggregates

Roller-compacted concrete contains fine and coarse aggregates. For concrete mixes reinforced with steel fibres, it is generally recommended that the nominal maximum size of the coarse aggregate is not larger than two-thirds of the fibre length and should not exceed one fifth of the minimum size of the members to be placed (JSCE, 1984). In this study, 14 mm nominal maximum size aggregate was used for all the mixes, regardless of fibre length, to facilitate comparisons.

The coarse and fine aggregates used were mainly crushed porphyritic andesite (granite type). Crushed aggregates are generally preferred in RCC as they reduce the risk of segregation, lead to better stability during the in situ rolling process and improve the bond between paste and aggregate. The upper and lower limits of the aggregate grading used (Figure 2) are based on the recommendations of the Portland Cement Association (PCA, 2006) as well as current UK RCC practice.

Recycled aggregates

Both recycled concrete aggregates (RCA) and recycled masonry aggregates (RMA) were investigated.

RECYCLED CONCRETE AGGREGATES

To demonstrate reusability of the proposed RCC/SFR-RCC pavements, aggregates were produced by crushing and grading previously tested RCC/SFR-RCC specimens.

To enable meaningful comparisons, the same gradation limits were used throughout the study. Since the aggregates obtained from crushing were mainly larger than 4 mm in diameter, river sand was added to complete the fine part of the gradation curve. Figure 3 shows a typical coarse aggregate obtained from crushed SFR-RCC with reused tyre wire fibres.

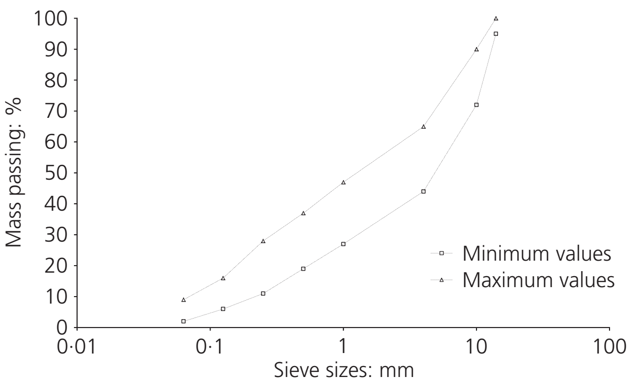

Figure 2. RCC aggregate sieve analysis

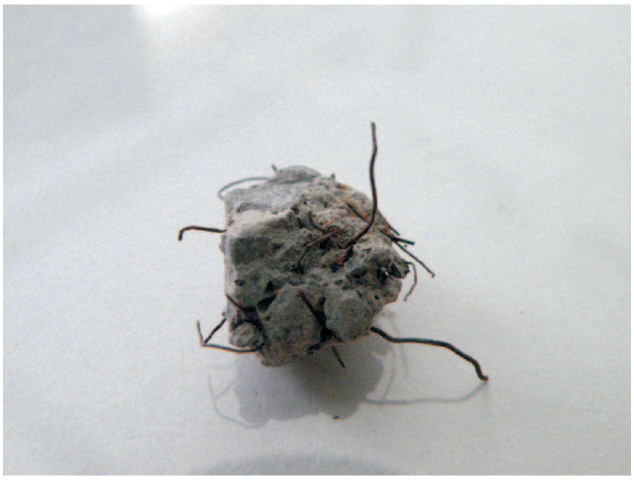

Figure 3. Typical RCA produced from tested SFR-RCC specimens with RTSF (nominal maximum size aggregate 14 mm)

RECYCLED MASONRY AGGREGATES

To assess the suitability of RMA in RCC, aggregates from demolition waste were used. The aggregate gradation was consistent with the rest of the mixes in this study. River sand was used for the fine part of the gradation curve. The main properties of these aggregates are summarised in Table 1.

Oven dried particle density: Mg/m^3	1·99
Saturated surface dried particle density: Mg/m^3	2·17
Apparent particle density: Mg/m^3	2·43
Water absorption: %	9·20
Flakiness	8

Table 1. Summary of properties of RMA

Roller-compacted concrete

Proportioning and mixing

The amount of water needed was determined using maximum dry density and optimum moisture content (OMC). For each RCC/SFR-RCC mix, the constituents were adjusted through several trial batches to achieve the mechanical properties required in pavement applications. The mix proportions of the RCC and SFR-RCC mixes used in this study are summarised in Table 2.

Aggregates were pre-soaked with the amount of water required to achieve the OMC and placed in an airtight container for 24 h. During mixing, the aggregates and cement were first mixed for 2 min. Steel fibres were then incrementally added (doses of 0·25% by mass of concrete) and mixing was terminated once all the fibres were added.

Compaction

Steel moulds were used to prevent mould deformations caused by the external compaction process. The RCC/SFR-RCC mix was

Cement: kg/m^3 of concrete	Water: kg/m^3 of concrete[a]	Aggregate blend: kg/m^3 of concrete	Steel fibres: % by mass of concrete	Steel fibres: kg/m^3 of concrete
150	124	2328	0	0
150	126	2320	1	25
150	129	2313	2	50
200	129	2269	0	0
200	137	2246	3	75
200	145	2224	6	150
200	153	2203	9	225
300	146	2133	0	0
300	153	2112	3	77

[a] Based on OMC.

Table 2. RCC/SFR-RCC mix proportions with three different cement contents

Figure 4. RCC compaction rig

Figure 5. Bending test set-up

placed up to the mid-depth of the mould; it reduced in height by a third when compacted. Each layer was consolidated for a maximum of 60 s or until a ring of mortar was formed around the tamper plate. Between two successive layers, the surface (top 5–10 mm) of the compacted layer was roughened to enhance bond characteristics. Overall, three layers were used.

COMPACTION APPARATUS

A special rig (Figure 4) was designed and manufactured to safely and reliably prepare laboratory samples that represent site RCC mixes. The rig comprises a mobile frame supporting a vibrating hammer (power input 1600 W, blow energy 7–27 J, blow rate under load 950–1900 blows/min) and a fixed dead load (100 kg). The hammer can receive circular or rectangular steel end tamping plates depending on the specimen being compacted. Vertical adjustment is attained by the use of a winch that incorporates a freewheel release catch (for rapid manual lowering).

Curing

Soon after casting, all specimens were covered with hessian/polythene sheet for 24 h and then demoulded and placed in a mist room (20°C and relative humidity $\geqslant$ 95%) until the day of testing.

Testing methodology

Compressive tests were carried out according to European standards (BSI, 2002, 2009) and flexural tests followed the Rilem recommendations (Rilem, 2002).

A four-point load arrangement was used instead of the three-point load arrangement recommended by Rilem (Figure 5). The use of a four-point load arrangement creates a region of constant moment and hence minimises overestimation of the bending resistance caused at the point of load application by the load-spreading effect (Timoshenko and Goodier, 1970). The two supports and the loading points consisted of articulated steel rollers of 30 mm diameter. Two of the rollers (one at the support and one at the device imposing the deformation) were capable of rotating freely around their axes and the longitudinal axis of the test specimen (Rilem, 2000). All rollers were placed on 5 mm thick steel plates to avoid local concrete crushing. The prismatic specimens were tested in a 1000 kN servo-hydraulic machine under crack mouth opening displacement (CMOD) control. The CMOD was controlled at a constant rare of 60 μm/min for CMOD = 0–0·1 mm and 0·2 mm/min for CMOD > 0·1 mm.

Test results

The abbreviation system adopted to describe the concrete mixes is as follows.

- The first term denotes the consistency of the mix (R for RCC).
- The second term indicates the cement type used (CEMII/A-L or LECr (low-energy calcium sulfoaluminate cement)) and the total binder content in kg/m^3.
- The third term denotes the fibre type and content in kg/m^3.
- The fourth term represents testing age.
- The fifth term represents aggregate type (na for natural aggregates and rma for recycled masonry aggregates).

For example R-CEMII/A-L200-MUND1/50-R1-3d-na is an RCC mix with 200 kg/m^3 of CEMII/A-L, 1% by mass dosage MUND1/50 fibre, tested at the age of 3 d and containing NA.

Fresh properties – optimum moisture content

Typical OMC curves for unreinforced RCC and SFR-RCC with 2% and 6% fibre dosages (by mass of concrete) are presented in Figure 6. For maximum density, water demand increases with fibre dosage, possibly due to the extra fibre surface area. This is also consistent with reports on increases in aggregate specific surface area for constant water/cement ratios that are known to yield reductions in strength (Newman and Teychenn, 1954). Mixes with water below the OMC resulted in severe fibre agglomeration.

The OMC was determined for the same basic RCC mix, but with varying fibre contents ranging from 1% to 6% by mass; the results are shown in Figure 7. The results reveal the following linear relationship between total moisture content and fibre content

$$\text{OMC}_{\text{SFR-RCC}} = \text{OMC}_{\text{RCC}} + 0{\cdot}125\text{FD} \qquad (1)$$

in which $\text{OMC}_{\text{SFR-RCC}}$ is the optimum moisture content of SFR-RCC, OMC_{RCC} is the optimum moisture content of RCC and FD is the fibre dosage by mass of concrete as a percentage.

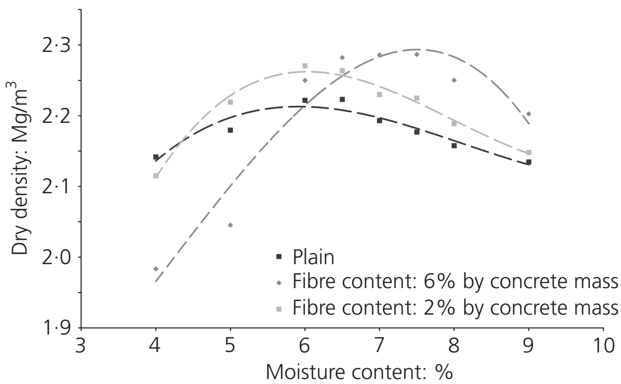

Figure 6. OMC curves for plain RCC and SFR-RCC with 2% and 6% fibre contents by mass of concrete

Effect of density on uniaxial compressive strength

The effect of density on the uniaxial compressive strength of SFR-RCC is shown in Figure 8, which presents results from 34 tests on SFR-RCC cubes (150 mm). In the range tested, the compressive strength f_c (MPa) appears to increase linearly with density ρ (kg/m^3) according to

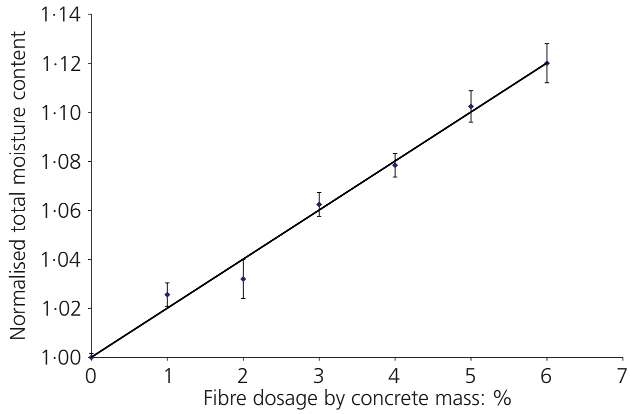

Figure 7. Normalised OMC for different fibre ratios, by mass of concrete

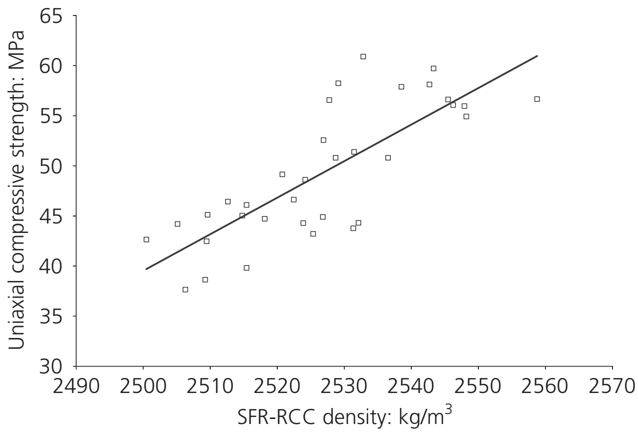

Figure 8. Effect of density on uniaxial compressive strength of SFR-RCC

2. $$f_\mathrm{c} = 0{\cdot}3646\rho - 872 \quad R^2 = 0{\cdot}62$$

According to the rule of mixtures, since steel is denser than concrete, the theoretical density of SFR-RCC is expected to increase with increasing fibre volume

3. $$\rho_{\mathrm{SFR\text{-}RCC_{theoretical}}} = \left[\frac{(m_\mathrm{f}/m_{\mathrm{SFR\text{-}RCC}})}{\rho_\mathrm{f}} + \frac{(m_{\mathrm{RCC}}/m_{\mathrm{SFR\text{-}RCC}})}{\rho_{\mathrm{RCC}}}\right]^{-1}$$

in which $m_{\mathrm{SFR\text{-}RCC}}$ is the mass of the composite, m_f is the mass of fibres, ρ_f is the density of the fibres, m_{RCC} is the mass of the matrix and ρ_{RCC} is the density of the matrix.

In practice, when the fibre dosage exceeds a certain limit (depending on fibre characteristics), density decreases due to increasing amounts of air trapped around the fibres and due to agglomeration.

The void ratio induced in RCC by fibre addition can be determined from

4. $$\upsilon_\mathrm{v} = \frac{\rho_{\mathrm{SFR\text{-}RCC_{theoretical}}} - \rho_{\mathrm{SFR\text{-}RCC_{expermental}}}}{\rho_{\mathrm{SFR\text{-}RCC_{theoretical}}}}$$

The experimental densities ($\rho_{\mathrm{SFR\text{-}RCC_{expermental}}}$) in Equation 4 were obtained according to BS EN 12390-7 (BSI, 2000). Figure 9 shows the effect of fibre dosage plotted against both density and calculated void ratio. It can be seen that for up to 3% fibre dosage, although the density increases by a small amount, the void ratio remains almost unchanged (approximately 3%). For higher fibre dosages the void ratio increases rapidly. Beyond the 5% fibre ratio, the density starts reducing despite the extra steel added in these mixes.

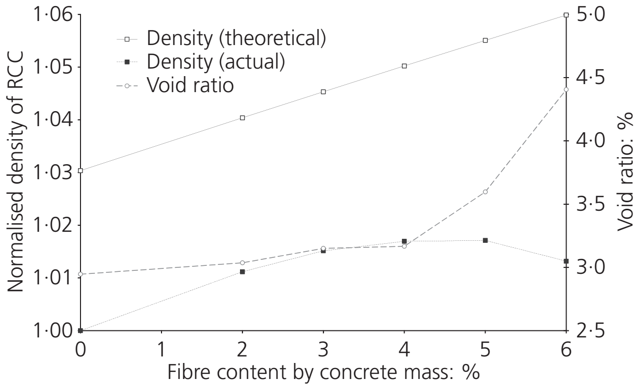

Figure 9. Effect of fibre dosage plotted against density and calculated void ratio

Compressive strength of RTSF-RCC

Table 3 shows the mean (from six specimens) compressive strength, standard deviation (SD) and coefficient of variation (CoV) for RCC mixes with three different RTSF length distributions at dosages of 1–9% (by concrete mass).

The use of RTSF fibres appears to affect the compressive strength of low cement content RCC adversely. Mixes with RTSF1-10 fibres lost less compressive strength, possibly due to fewer issues with agglomeration.

Mix	Mean compressive strength: MPa	SD: MPa	CoV: %
R-CEMII/A-L200-RTSF1-10-R1-3d-na	14·5	1·5	10·3
R-CEMII/A-L200-RTSF1-10-R2-3d-na	13·5	2·0	14·8
R-CEMII/A-L200-RTSF1-10-R3-3d-na	13·4	0·4	3·0
R-CEMII/A-L200-RTSF1-10-R6-3d-na	11·2	0·5	4·5
R-CEMII/A-L200-RTSF1-10-R9-3d-na	10·0	0·1	0·4
R-CEMII/A-L200-RTSF1-20-R1-3d-na	12·6	1·3	10·3
R-CEMII/A-L200-RTSF1-20-R2-3d-na	11·1	1·5	13·5
R-CEMII/A-L200-RTSF1-20-R3-3d-na	10·6	1·4	13·2
R-CEMII/A-L200-RTSF1-20-R6-3d-na	8·6	0·3	3·5
R-CEMII/A-L200-RTSF1-20-R9-3d-na	6·5	0·1	0·2
R-CEMII/A-L200-RTSF5-40-R1-3d-na	9·9	1·8	18·2
R-CEMII/A-L200-RTSF5-40-R2-3d-na	8·6	0·1	1·2
R-CEMII/A-L200-RTSF5-40-R3-3d-na	7·9	0·3	3·8
R-CEMII/A-L200-RTSF5-40-R6-3d-na	4·6	0·3	6·5

Table 3. Uniaxial compressive strength results of SFR-RCC mixes at various RTSF types and dosages

Table 4 shows the effect of 'pre-wetting' the RTSF in the RCC matrix. The mixes with wetted fibres (six specimens per mix) performed better, most probably due to the effect of extra paste forming around a wet fibre.

Compressive strength of RCC with manufactured fibres

Table 5 shows the mean compressive strength values, SD and CoV for SFR-RCC mixes reinforced with M2H1/50, M2C1/54 and MUND1/50 fibres. The compressive strength of these mixes was less affected (slight reduction, in the range 5–10%) by fibre content, possibly due to a reduction in trapped air around the fibres, except for mixes with 4% fibre which suffered severe balling. The undulated MUND1/50 fibres appear to reduce strength at a faster rate, meaning that the wavy shape of this fibre type is more prone to inducing voids.

Compressive strength of RCC with fibre blends

Table 6 summarises the mean compressive strength, SD and CoV values for mixes with RTSF1-10 fibres combined (at equal fractions) with M2C1/54 fibres at fibre dosages of 1%, 2% and 3% by mass. The results indicate that replacing 50% RTSF with manufactured fibres in low paste content mixes improves performance; the strength reductions associated with the increased fibre dosage are similar to those observed with mixes with 100% manufactured fibres.

Compressive strength of RCC with RA

To avoid the issues associated with SFR-RCC mixes with low cement contents, a higher cement content (300 kg/m^3) was adopted for the mixes with RA. Despite the additional 100 kg/m^3 of cement, the mixes with RMA achieved relatively low uniaxial

Mix	Mean compressive strength: MPa	SD: MPa	CoV: %
R-CEMII/A-L200-RTC5-40-R2-3d-na (dry)	8·6	0·1	1·4
R-CEMII/A-L200-RTC5-40-R2-3d-na (wetted)	11·9	1·8	15·5

Table 4. Compressive strength results for RTSF-RCC with 'dry' and 'wetted' fibres

Mix	Mean compressive strength: MPa	SD: MPa	CoV: %
R-CEMII/A-L200-M2H1/50-R1-3d-na	16·9	0·8	4·7
R-CEMII/A-L200-M2H1/50-R2-3d-na	16·4	0·2	1·2
R-CEMII/A-L200-M2H1/50-R3-3d-na	14·8	2·0	13·5
R-CEMII/A-L200-M2C1/54-3d-R1-na	16·7	0·2	1·2
R-CEMII/A-L200-M2C1/54-3d-R2-na	15·8	0·04	0·3
R-CEMII/A-L200-M2C1/54-3d-R3-na	14·1	0·4	2·9
R-CEMII/A-L200-MUND1/50-3d-R1-na	16·4	0·5	3·1
R-CEMII/A-L200-MUND1/50-3d-R2-na	15·3	1·7	11·1
R-CEMII/A-L200-MUND1/50-3d-R3-na	12·4	1·0	8·1
R-CEMII/A-L200-MUND1/50-3d-R4-na	9·0	0·04	0·4

Table 5. Uniaxial compressive strength results of SFR-RCC mixes with various manufactured fibre types and contents

Mix	Mean compressive strength: MPa	SD: MPa	CoV: %
R-CEMII/A-L200-M2C1/54+RTSF1-10-R1-3d-na	15·8	1·1	6·9
R-CEMII/A-L200-M2C1/54+RTSF1-10-R2-3d-na	15·7	0·4	2·5
R-CEMII/A-L200-M2C1/54+RTSF1-10-R3-3d-na	13·4	1·9	14·2

Table 6. Uniaxial compressive strength results of SFR-RCC mixes with hybrid fibres

compressive strength results (Table 7), with a mean value (six specimens) of 16·7 MPa (SD = 0·4, CoV = 2·4%), after 7 d of curing. This highlights the inferior properties of the RMA aggregates. The addition of RTSF1-15 fibres (3% by mass) enhanced the compressive strength performance by 55%, realising compressive strength values equivalent to those obtained by plain concrete mixes with NA. Contrary to what was observed for mixes with low paste contents, when the cement content increased, the adverse effect of fibres was mitigated. For these mixes, RTSF seems to be particularly effective as, due to the smaller dimensions of the fibres, there is a larger number of fibres per reinforcing ratio when compared with standard manufactured fibres (e.g. 30 times the number of typical 1 mm diameter 50 mm long fibres). The denser RTSF configuration gives a higher probability of fibres bridging weak regions, thus delivering a regulatory effect. This seems to be very beneficial for matrixes with inferior quality materials.

Table 8 presents the results obtained from RCC/SFR-RCC mixes at various RCA/NA ratios. These results indicate that RA sourced from good-quality concrete could replace NA at any ratio without considerable reduction in compressive strength. This observation is consistent for both RCC and SFR-RCC mixes.

Bending performance of RCC with RTSF

Figures 10 and 11 show the flexural test results for mixes with RTSF. The curves shown are averages of results from six specimens. These results show that an increase in fibre dosage (even up to levels that reduced compressive strength) has a positive effect and substantial contribution both in terms of flexural strength and post-peak load-bearing capacity. Mixes with the longer fibres (RTSF5-40) demonstrated higher strength (Table 9), toughness (Table 10) and more stable post-peak load behaviour than mixes with shorter fibres (RTSF1-10). A measurement of toughness is given by the $R_{0 \cdot 5}$ value, representing the ratio of the average load resisted when the beam deflects to 0·5 mm to the load at first crack.

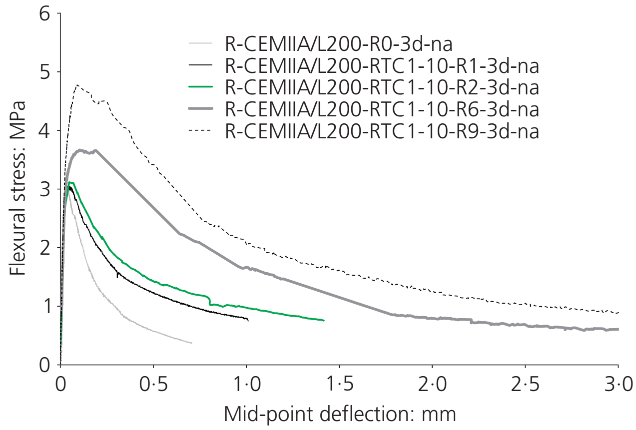

Figure 10. Bending test results for SFR-RCC mixes at various RTSF1-10 dosages in low cement content matrix (200 kg/m^3 of CEMII/A-L) at age 3 d

Mix	Mean compressive strength: MPa	SD: MPa	CoV: %
R-LECr300-R0-7d-na	27·6	0·2	0·7
R-LECr300-R0-7d-rma	16·7	0·4	2·4
R-LECr300-RTSF1-15-R3-7d-rma	25·9	0·2	0·8

Table 7. Effect of RTSF on RCC matrix with RMA (cement content 300 kg/m^3)

Mix	Mean compressive strength: MPa	SD: MPa	CoV: %
R-LECr300-R0-28d-100%na,0%rca	28·0	1·0	3·6
R-LECr300-R0-28d-70%na,30%rca	27·6	1·0	3·6
R-LECr300-R0-28d-30%na,70%rca	27·1	1·3	4·8
R-LECr300-R0-28d-0%na,100%rca	27·2	0·7	2·6
R-LECr300-RTSF5-25-R0-28d-100%na,0%rca	34·0	1·0	2·9
R-LECr300- RTSF5-25-R0-28d-70%na,30%rca	33·0	0·1	0·3
R-LECr300- RTSF5-25-R0-28d-30%na,70%rca	32·8	0·9	2·7
R-LECr300- RTSF5-25-R0-28d-0%na,100%rca	31·7	0·6	1·9

Table 8. Effect of different RCA/NA ratios on RCC and SFR-RCC mixes (cement content 300 kg/m^3)

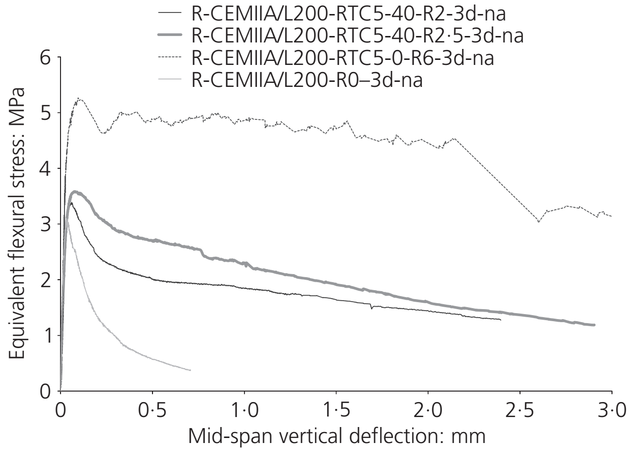

Figure 11. Bending test results for SFR-RCC mixes at various RTSF5-40 dosages in low cement content matrix (200 kg/m^3 of CEMII/A-L) at age 3 d

Mix	$R_{0\cdot5}$
R-CEMIIa/L200-R0-3d-na	0·6
R-CEMIIa/L200-RTSF1-10-R1-3d-na	0·8
R-CEMIIa/L200-RTSF1-10-R2-3d-na	0·9
R-CEMIIa/L200-RTSF1-10-R6-3d-na	1·6
R-CEMIIa/L200-RTSF1-10-R9-3d-na	1·8
R-CEMIIa/L200-RTSF5-40-R2-3d-na	1·0
R-CEMIIa/L200-RTSF5-40-R2·5-3d-na	1·2
R-CEMIIa/L200-RTSF5-40-R6-3d-na	2·0

Table 10. Ductility of SFR-RCC mixes at various RTSF1-10 dosages in low cement content matrix (200 kg/m^3 of CEMII/A-L)

It has been demonstrated that by using different volumes of RTSF in RCC, flexural performance ranges from softening to even elasto-plastic (at relatively high volumes).

Full-scale proof of concept

To demonstrate the feasibility of reinforcing RCC with RTSF and manufactured fibres at an industrial scale, a trial was conducted at a site in London. A 20 m long, 5 m wide, 200 mm deep pavement was constructed on a cement-bound material subbase. The RCC mix design comprised ordinary Portland cement at 300 kg/m^3, water at OMC (6%) and granite aggregates. Half of the pavement was constructed with flat-end fibres (50 kg/m^3) and the rest with RTSF4-24 (50 kg/m^3). The density of the pavement as measured by a nuclear density gauge was 2460 kg/m^3. The fibres were introduced into the concrete mix at a conventional concrete batching plant using pan mixers and the dispersion appeared to be satisfactory.

Transversal joints were saw cut every 3 m and filled with bitumen, just after paving when the concrete was still in its fresh state. A 10 t vibratory roller was used to apply final compaction and seal the joints. This proved to be an efficient way of introducing joints.

Six cores (diameter 150 mm, length 300 mm) were extracted from the finished pavement and an equal number of cylindrical specimens (identical to the cores) were cast alongside the pavement with the compaction frame developed for lab use (described in detail earlier in the paper). The densities of cores and cast specimens were compared (according to BS EN 12390-7 (BSI, 2000) and the results were identical (2% difference), confirming the suitability of the compaction frame developed (average compressive strength values of 25 MPa at 28 d were obtained).

Visual examination of the surface of the finished pavement was also conducted. It was concluded that RTSF integrate better in the RCC matrix than manufactured fibres, with no issues of fibre clustering (Figure 12). Overall, the trial demonstrated that RTSF could be integrated successfully in RCC at an industrial scale using conventional equipment.

Conclusions

The feasibility of reinforcing roller-compacted concrete (RCC) with steel fibres was investigated experimentally and practical

Mix	Flexural strength: MPa	SD: MPa	CoV: %
R-CEMIIa/L200-R0-3d-na	3·1	0·1	3·2
R-CEMIIa/L200-RTSF1-10-R1-3d-na	3·1	0·1	3·2
R-CEMIIa/L200-RTSF1-10-R2-3d-na	3·1	0·1	3·2
R-CEMIIa/L200-RTSF1-10-R6-3d-na	3·7	0·5	13·5
R-CEMIIa/L200-RTSF1-10-R9-3d-na	4·8	0·1	2·1
R-CEMIIa/L200-RTSF5-40-R2-3d-na	3·4	0·1	3·0
R-CEMIIa/L200-RTSF5-40-R2·5-3d-na	3·6	0·14	3·9
R-CEMIIa/L200-RTSF5-40-R6-3d-na	5·3	0·18	3·4

Table 9. Flexural strengths of SFR-RCC mixes at various RTSF1-10 dosages in low cement content matrix (200 kg/m^3 of CEMII/A-L)

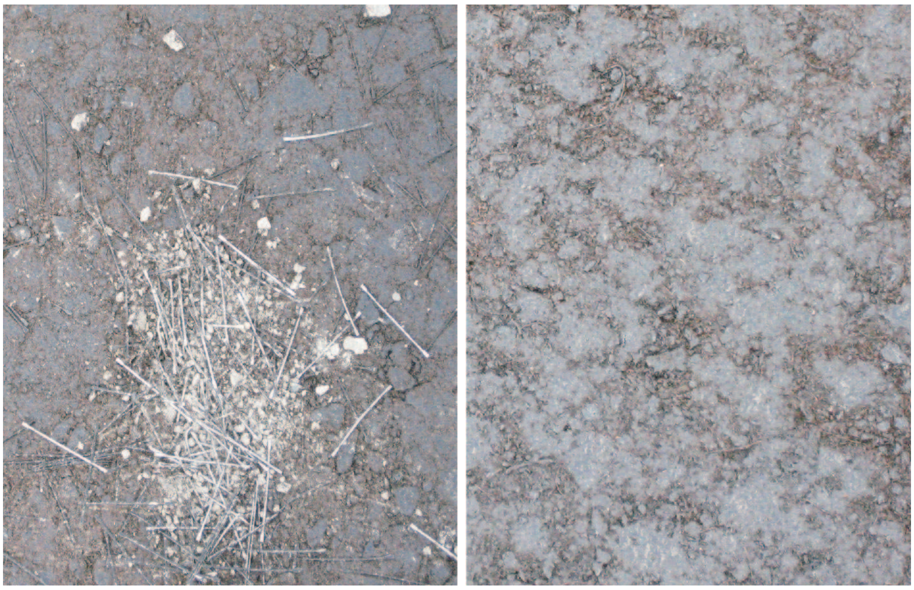
(a) (b)

Figure 12. Fibres on pavement surface: (a) manufactured; (b) RTSF

aspects were confirmed with a proof-of-concept trial. The results reveal the following.

- The addition of fibres in a concrete matrix of low cement content (200 kg/m^3) leads to void formation, which has a negative impact on early-age compressive strength (strength reductions of 20–70%). Manufactured fibres appear to have less negative impact than reused tyre steel fibres (RTSF).
- Mixes with higher cement contents (300 kg/m^3) appear to be less adversely affected due to the extra cement paste available to fill any voids and prevent fibre agglomeration, resulting in a denser concrete matrix configuration.
- Plain concrete mixes with recycled masonry aggregates achieved 40% lower compressive strength, compared to mixes made with natural aggregates (NA). The compressive strength values of these mixes considerably improved (+55%) with the addition of 3% (by mass) RTSF fibres, achieving strength values comparable to those obtained from mixes made entirely from NA.
- Mixes made of high-quality recycled concrete aggregates (granite type) had very similar strength to specimens entirely made of NA for both RCC and SFR-RCC mixes.
- Despite the poor compressive strength performance of early-age low cement content SFR-RCC, bending performance was not adversely affected and substantial increases in both strength and post-cracking load capacity were observed for fibre dosages up to 225 kg/m^3.
- Fibre integration in RCC at an industrial scale proved to be feasible. RTSF fibres integrated better in RCC than larger manufactured fibres, which had a tendency to appear on the surface.

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