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Fatigue resistance and cracking mechanism of concrete pavements reinforced with recycled steel fibres recovered from post-consumer tyres

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ABSTRACT

Recycled steel fibres recovered from post-consumer tyres can be used as reinforcement in concrete to enhance its post-cracking flexural behaviour and may also improve its fatigue behaviour. This paper aims to examine the use of recycled steel fibres as fatigue reinforcement for concrete pavements, based on an experimental investigation. Concrete prisms were subjected to cyclic third-point flexural loads at a frequency of 15 Hz, at maximum stress levels of 0.5, 0.7 and 0.9. Two types of mixes, conventional and roller compacted concrete, and two recycled fibre contents, 2% and 6% by mass of concrete were used. Unreinforced and industrially produced fibre reinforced concrete mixes were also tested for comparison purposes. The recycled fibres were found to improve the fatigue behaviour of concrete, especially for conventional plastic concrete mixes. Recycled fibres improve fatigue by restraining the propagation of micro-cracks into meso and macro-cracks, whilst industrially produced fibres are more efficient at arresting macro-cracks. For enhanced fatigue performance, it is recommended that recycled fibres should be used in combination with industrially produced fibres. Predictive models are developed using a probabilistic approach. The results show that the use of recycled steel fibres may contribute to a reduction of up to 26% of pavement thickness, when considering the influence of fatigue alone.

1. Introduction

Compared to asphalt pavements, concrete pavements (jointed or continuously reinforced) can offer a more sustainable solution due to lower maintenance [1,2] and other environmental benefits, such as reductions in lifetime energy consumption and volume of aggregates used in construction [3]. However, the higher initial cost of such pavements still prevents their more extensive use, mainly due to cost of cement and reinforcement. Nonetheless, increasing costs of bitumen are likely to reduce the cost differential in the near future [4].

Industrially produced steel fibres (IF) can be added to plain concrete to improve its post-cracking flexural strength and fatigue performance or to replace conventional reinforcement in continuously reinforced slabs. The use of fibres can lead to a reduction in pavement depth, thus reducing overall costs, as well as, speeding up the on-site processes and reducing trip hazards [5,6]. However, concrete pavements reinforced with IF have higher material costs than those with conventional reinforcement mainly due to the larger volume of steel required to achieve the desired mechanical characteristics [7]. The recently developed alternative of recycled steel fibres recovered from post-consumer tyres (RF) can lead to a cheaper fibre solution with significant environmental benefits [8,6].

Roller compacted concrete (RCC) may also be used as a sustainable alternative for road construction due to lower cement consumption and faster construction [9,10]. A combination of both RCC and RF could lead to an ideal solution in terms of environmental benefits, cost reduction and faster construction of pavements [11,12,6].

Even though some work has been done on the mechanical performance of steel fibre reinforced concrete (SFRC) with recycled fibres [13,8,14–19] including work on the combined use of RCC and RF [11,20–22,6], there is still lack of studies on the fatigue performance of concrete, using micro, meso and macro-fibres.

Large numbers of cyclic loads as induced by traffic can reduce the performance of concrete by propagating cracks, deteriorating the elastic properties, increasing the fatigue fracture toughness [23–25] and leading to the brittle failure of the material. Fatigue deterioration of plain concrete has also been attributed to cyclic creep of the compression zone of the concrete [26,27].

In well designed SFRC, fibres can control crack propagation [28,24,25,29], thus increasing the endurance life of the material

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and contributing to a more ductile behaviour. The main fatigue failure mechanism in SFRC is a result of bond degradation between the fibres and the matrix [24,25], but fatigue fracture of the fibres can also occur [24].

Fatigue of SFRC is also affected by the characteristics of the mix as well as fibre content, type and geometry [28,25]. Hence, due to the geometric characteristics of the RF (which are shorter and thinner than commonly used IF), it is expected that the fatigue behaviour of SFRC with recycled fibres will differ compared with SFRC containing IF. This is supported by results found in [29] when comparing micro with meso and with macro-fibres.

This paper will initially present the materials and methods used in the experimental programme carried out to test concrete prisms subjected to cyclic flexural loads. The results and discussion are presented in terms of *S*–*N* curves, crack mechanism and fatigue probabilistic analysis. The possible design implications evaluated by means of a practical example are also presented.

2. Research significance

This research aims to develop an understanding of the fatigue behaviour of concrete pavements reinforced with recycled steel fibres recovered from post-consumer tyres. RF are thinner and shorter than conventional IF and are expected to work better at the micro-crack level. The fatigue behaviour was mainly investigated through experimental tests on concrete prisms subjected to cyclic flexural loads. Crack mouth opening measurements were made during the tests. RF are considerably cheaper than IF and if they are found to perform well structurally, they can provide an environmentally friendlier alternative to IF.

3. Materials and methods

Seven concrete mixes were examined in this research, and their mix proportions are shown in Table 1. Both RCC and conventional plastic concrete (CON) were used, as well as RF and IF. A binder combination of 80% of CEM I and 20% of PFA was adopted for all mixes. CON mixes were cast with river (fluvial dragged) aggregates, whilst RCC mixes were cast with crushed basalt. The aggregates for RCC mixes were saturated prior to casting. The gradation of aggregates is shown in Fig. 1.

The IF used were made of 1 mm cold drawn wire with a cone forged at each end, and a length of 54 mm. The nominal tensile strength of IF was around 1100 MPa. The RF were recovered from the mechanical treatment of post-consumer tyres [30] and had a mean diameter of 0.2 mm and a variable length (90% of the fibres had length in the range between 3 and 22 mm). The tensile strength of RF can be up to 2000 MPa [14]. Fig. 2 shows the recycled and industrial fibres.

CON mix specimens were compacted by an external vibrator while the RCC mix specimens were compacted in the laboratory by using a hydraulic hammer attached to a specially developed steel frame (as elaborated in Neocleous et al. [6]). In total, 118 prismatic specimens (dimensions: 150 × 150 × 550 mm) were cast and tested, including the ones used for static and dynamic tests. Specimens were tested against fatigue loading when they were at least 4 months old.

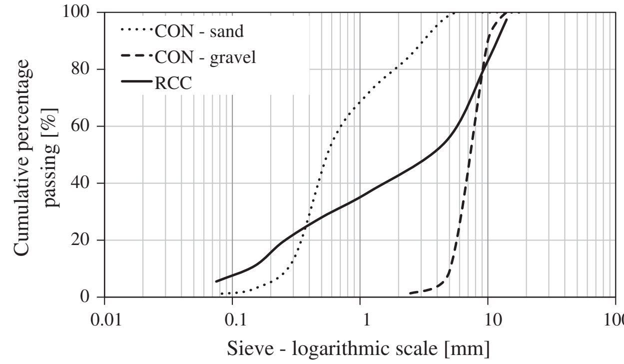

Fig. 1. Gradation curves of aggregates.

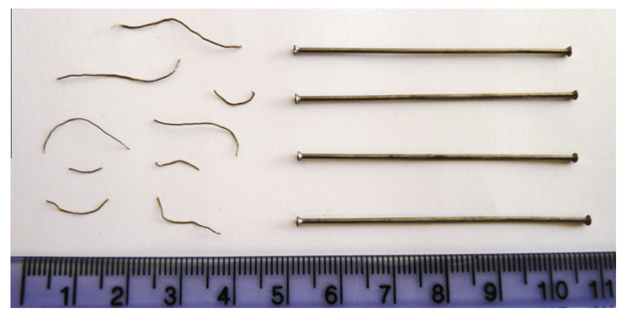

Fig. 2. Appearance of (a) RF and (b) IF.

Since fatigue tests are expensive and time-consuming, the tests were performed in a three-specimen setup, with loads applied in a third-point configuration, as shown in Fig. 3. The fatigue loads were applied to the three specimens simultaneously, and the load was transferred from one specimen to another by rollers. Vertical displacements were recorded in each specimen by transducers held by specially manufactured yokes.

Three flexural stress levels (*S*) – ratio between the dynamic flexural strength to the static peak flexural strength – were used: 0.5, 0.7 and 0.9 (0.6, 0.7 and 0.8 for mix RCC–6RF). At least three specimens were tested per mix per stress level, as it is shown in the experimental test matrix in Table 2. Cyclic loads were applied at a frequency of 15 Hz, with a minimum of 10% of the peak load being maintained on the specimens. The loads were applied until one of the three specimens failed or until they reached 2 million cycles, a limit commonly used in the literature for concrete fatigue [31,28,32,25]. In case of failure, the failed specimen was removed from the fatigue setup and a new specimen took its position. This procedure was repeated until two non-failed specimens remained for each mix and stress level; these specimens were then tested independently (without the three-specimen configuration).

Table 1
Description of mix proportions.

Mix	Type of mix	Cement (kg/m^3)	PFA (kg/m^3)	Aggregate (kg/m^3)	Fibre content (% by mass of concrete, kg/m^3)	Water (kg/m^3)	w/c
CON-0	CON	305	75	1830 (45% fine)	0%, –	135	0.35
CON–2RF	CON	305	75	1830 (45% fine)	2%, 46.9	135	0.35
CON–6RF	CON	305	75	1830 (45% fine)	6%, 140.7	135	0.35
RCC-0	RCC	240	60	2125	0%, –	150	0.50
RCC–2IF	RCC	240	60	2125	2%, 51.5	150	0.50
RCC–2RF	RCC	240	60	2125	2%, 51.5	150	0.50
RCC–6RF	RCC	240	60	2100	6%, 153.3	155	0.52

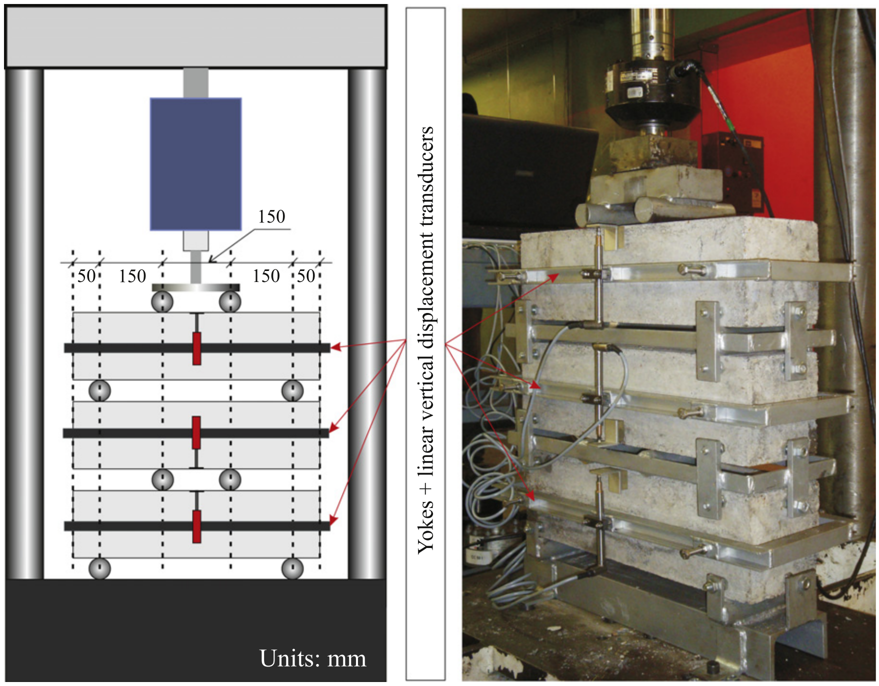

Fig. 3. Fatigue setup of specimens.

Table 2
Experimental test matrix.

Mix	Type of mix	Fibre content and type	Stress level	Number of specimens – dynamic tests	Number of specimens – static tests
CON-0	CON	–	0.5	6	2
			0.7	6	
			0.9	4	
CON–2RF	CON	2% Recycled	0.5	5	2
			0.7	6	
			0.9	4	
CON–6RF	CON	6% Recycled	0.5	6	2
			0.7	5	
			0.9	4	
RCC-0	RCC	–	0.5	6	2
			0.7	5	
			0.9	4	
RCC–2IF	RCC	2% Industrially produced	0.5	4	2
			0.7	4	
			0.9	3	
RCC–2RF	RCC	2% Recycled	0.5	6	2
			0.7	6	
			0.9	4	
RCC–6RF	RCC	6% Recycled	0.6	5	2
			0.7	6	
			0.8	5	

4. Results and discussion

4.1. S–N approach

To determine the load level for each stress level, two specimens from each mix were subjected to third-point static flexural tests [33]. The peak flexural loads obtained for each mix are shown in Table 3.

During the fatigue tests, the number of cycles to failure (N) was recorded for each specimen. For specimens reaching 2 million cycles without failing, N is recorded as 2 million. Figs. 4 and 5 show the S–N curves for CON and RCC mixes, respectively. Table 4 presents the S–N equations and their respective coefficient of correlation as well as the number of un-failed specimens per mix. It is important to note that high deviations are usually expected in fatigue tests on FRC because of the random orientation of fibres [34,35] and also because the specimens tested against fatigue are not the same tested to determine the static peak flexural load [29].

The figures show that RF improve the fatigue performance of concrete, either by increasing its endurance life or by increasing the stress level for a specific number of cycles. The amount of 2% by mass seems to give the best fatigue performance for CON mixes. Similar conclusions for a critical IF content were also reported in the literature [31,36,25]. When subjected to high stress levels (above 0.7), RCC-0 mix had better performance than reinforced RCC mixes, which is possibly a result of good aggregate interlock due to the use of crushed aggregates and high compaction energy

Table 3
Peak load from static flexural test.

Mix	CON-0	CON–2RF	CON–6RF	RCC-0	RCC–2IF	RCC–2RF	RCC–6RF
Peak load per specimen (kN)	68.1, 68.3	48.5, 52.2	73.5, 81.7	61.6, 65.8	69.0, 92.5	65.4, 69.6	76.8, 79.9
Average peak load (kN)	68.2	50.4	77.6	63.7	80.8	67.5	78.4

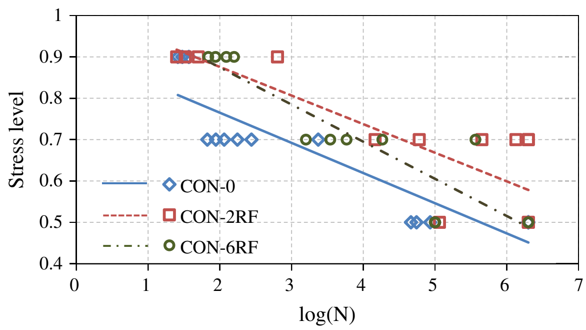

Fig. 4. *S–N* curves for CON mixes.

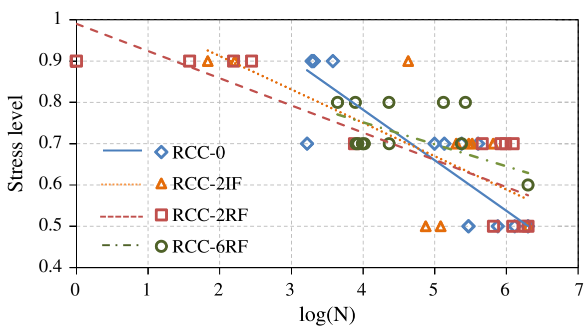

Fig. 5. *S–N* curves for RCC mixes.

applied to the mixes. The addition of fibres in RCC appears to increase the amount of voids in the concrete, thus reducing the aggregate interlock effect. All RCC mixes with fibres show similar behaviour, with better fatigue resistance than plain concrete at stress levels lower than 0.7, possibly due to better crack control.

4.2. Vertical displacement analysis

Vertical displacements were obtained every 30 min, at a frequency of 400 Hz for a period of 10 s, due to data storage limitations. Typical amplitude displacement curves are shown in Figs. 6 and 7, for CON and RCC specimens, respectively. It should be noted that the results are shown for single specimens, (a) reaching 2 million cycles (un-failed) and (b) failing specimens. The majority of specimens subjected to stress level of 0.9 (0.8 for RCC–6RF) and some subjected to the stress level of 0.7 failed fairly rapidly (less than 30 min), hence, the figures only show displacements at the lower stress levels of 0.5 and 0.7 (when available).

On initial examination, recycled SFRC specimens appear to have a more brittle failure behaviour than specimens with IF. RF are usually able to resist displacements up to two times the predicted static displacement at the given stress level, followed by an abrupt failure. IF, on the other hand, are able to sustain displacements up to 10 times the predicted static displacement, and this may occur over a considerably large number of cycles.

The general pattern of amplitude of vertical displacements is shown diagrammatically in Figs. 8 and 9, for RF and IF, respectively. The pattern of amplitude displacement for RF concrete specimens shows a small initial increase in the displacements, probably due to the release of internal stresses, such as the ones caused by shrinkage and other thermal influences. The initial increase in displacements for IF concrete specimens is much higher than for RF and comprises not only the release of any internal stresses, but also the propagation of micro-cracks into meso and macro-cracks.

The second stage in the pattern of displacements for failed RF concrete specimens is characterised by a stabilised phase during which fibres appear to hold well the existing micro-cracks, preventing their propagation into meso-cracks. Micro-cracks are inherent in concrete (due to voids and shrinkage) and develop further during loading. This means that RF specimens with higher volume of voids are likely to have more initial micro-cracks and this may increase the rate at which the displacements increase over this second stage. During the second stage in the pattern of displacements for IF concrete specimens, the fibres appear to control the propagation of macro-cracks. Due to the cracked condition of the concrete, this stage is not as stabilised as the second stage for RF concrete specimens, and the displacements increase gradually in a more or less linear rate. Nonetheless, the IF are still able to prevent the unstable propagation of cracks. By the end of the second stage, most of the macro-cracks are already well formed and some of the fibres are fully utilised (mobilised from end to end), as explained below. Then a sudden change in the behaviour occurs, represented by an inflexion point at the end of the semi-stabilised curve and the unstable propagation of cracks takes places.

For the RF concrete specimens, the last stage of displacement pattern is shorter than the second stage and is dominated by the propagation of micro-cracks into meso-cracks, represented by a rapid increase in the displacements during a relatively low number of cycles. After several cycles holding meso-cracks, the mechanical friction between the fibres and the matrix deteriorates, and the

Table 4
Number of un-failed specimens after 2 million cycles and fatigue *S–N* equations.

Mix	Number of un-failed specimens			*S–N* equation (and coefficient of correlation – R^2)
	0.5	0.7	0.9	
CON-0	3	–	–	$\log(N) = -13.7S + 12.5$ (0.80)
CON–2RF	4	2	–	$\log(N) = -14.5S + 14.7$ (0.70)
CON–6RF	4	–	–	$\log(N) = -11.1S + 11.7$ (0.86)
RCC-0	2	–	–	$\log(N) = -8.2S + 10.4$ (0.77)
RCC–2IF	1	–	–	$\log(N) = -12.4S + 13.3$ (0.53)
RCC–2RF	2	–	–	$\log(N) = -15.2S + 15.0$ (0.71)
RCC–6RF	5	–	–	$\log(N) = -18.8S + 18.1$ (0.48)

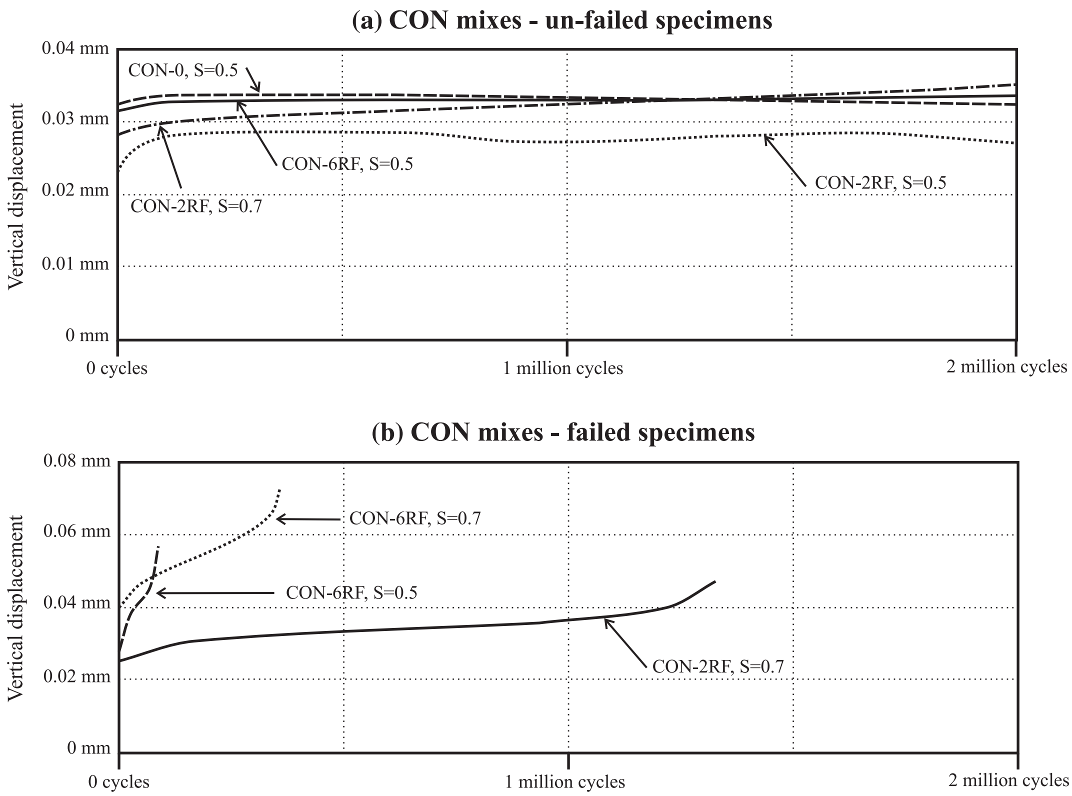

Fig. 6. Typical vertical displacement curves for CON mixes: (a) un-failed specimens and (b) failed specimens.

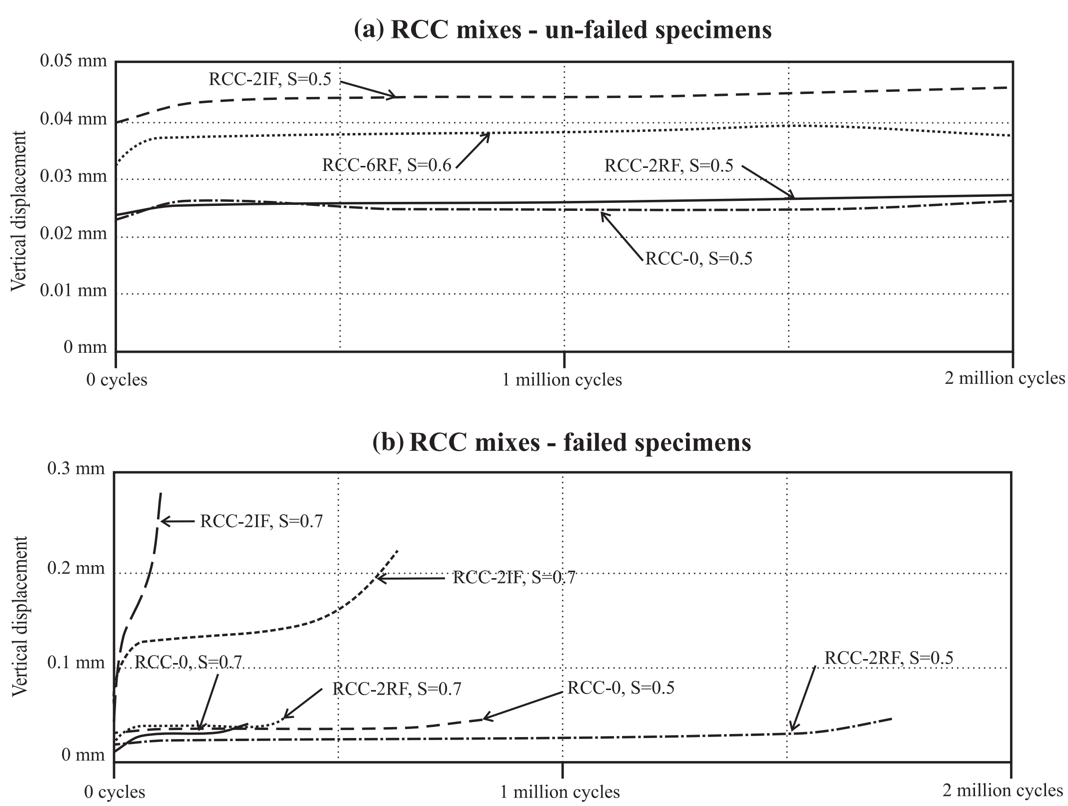

Fig. 7. Typical vertical displacement curves for RCC mixes: (a) un-failed specimens and (b) failed specimens.

meso-cracks rapidly propagate into macro-cracks (exceeding 0.1 mm) and quickly lead to pullout of these relatively short fibres. This is illustrated in Fig. 10 for mix RCC–6RF (S = 0.8) at which the displacements were recorded continuously. On examining the broken specimens, further evidence was found to suppose this hypothesis as pulled out fibres could be seen on the fracture sur-

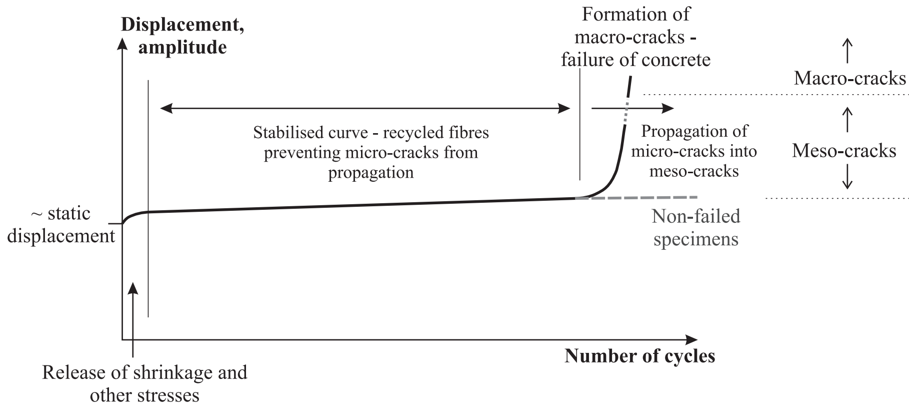

Fig. 8. Pattern of amplitude of displacements for concrete reinforced with RF.

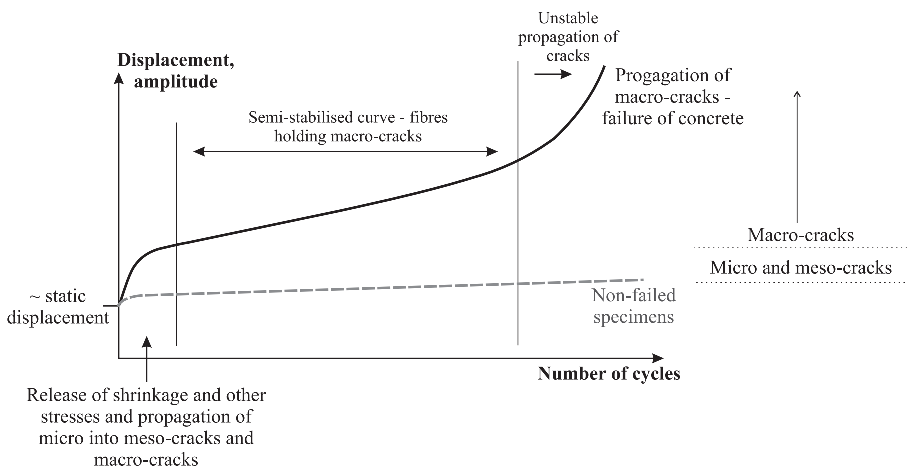

Fig. 9. Pattern of amplitude of displacements for concrete reinforced with IF.

face (Fig. 11a). Fig. 10 also shows, for comparison purposes, the displacement pattern for RCC–2IF ($S = 0.5$), which confirms that the two types of fibres work in a different way by arresting cracks at different stages. In addition, the figure shows that the final displacement of the RF specimen is larger than was evident from the other RF results, nonetheless the large displacements take place over a very short number of cycles, which was not captured by the intermittent measurements taken. It should be pointed out that in a pavement structure which fails due to the development of multiple yield lines, large inelastic displacements will lead to redistribution of stresses and, as a result, the failure of the pavement will not be as brittle as that of the material.

For the IF SFRC specimens, the last stage takes place when displacement exceeds 0.2 mm. At this stage, the IF are still able to hold some of the cracks together, thus increasing the fatigue life of the cracked concrete. The two last stages of the displacement pattern for IF concrete specimens are much longer compared to the first stage, confirming that IF SFRC has better performance in arresting macro-cracks than in arresting micro and meso-cracks [29]. The displacements at which the IF SFRC specimens fail are too low for considerable slip of the fibres to take place. This particular IF type with the end cones is very well anchored and the evi-

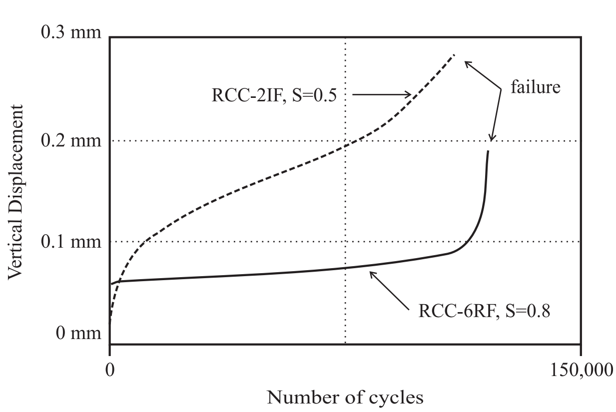

Fig. 10. Continuously recorded vertical displacement curve of RCC–6RF, $S = 0.8$.

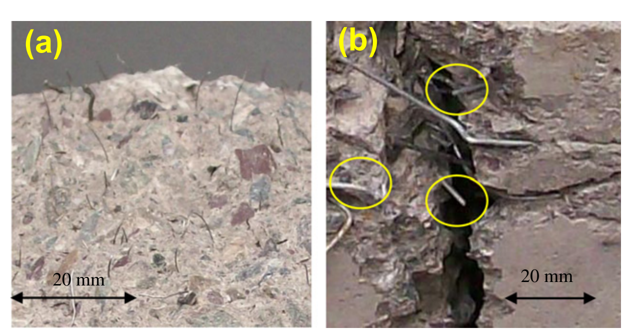

Fig. 11. Fractured surface of (a) RF SFRC and (b) IF SFRC specimens.

Table 5
Ranking of specimens for probabilistic analysis (mix RCC-0 at stress level of 0.5).

i	N_i	$\text{Log}_{10}(N_i)$	Mean μ and standard deviation σ of $\log(N_i)$	$\frac{\lvert\log(N_i)-\mu\rvert}{\sigma}$	Remark
1	295,400	5.47		1.18	Discarded
2	296,050	5.47		1.18	Discarded
3	756,903	5.88	μ = 5.92	0.11	OK
4	1,305,150	6.12	σ = 0.38	0.50	OK
5	2,000,000	6.30		0.99	OK
6	2,000,000	6.30		0.99	OK

Table 6
Ranked specimens in terms of N ($\log N$) according to stress level for mix RCC-0.

i	Stress level			$p_f = \frac{i}{(n+1)}$
	0.5	0.7	0.9	
1	756,903	36,850	1915	0.2
2	1,305,150	99,175	1975	0.4
3	2,000,000	136,072	2056	0.6
4	2,000,000	402,839	3791	0.8

dence points towards a failure of the fibres at the cone ends, as also highlighted in Fig. 11b.

The crack behaviour for un-failed specimens is similar for both RF and IF concrete and in both cases micro cracks are controlled. This is because at the initial stage, the matrix itself is also contributing in preventing the propagation of micro-cracks. A similar pattern of displacements is also observed for plain concrete in Figs. 6a and 7a and this supports the above hypothesis.

It is logical to conclude from the above discussion that a combination of both RF and IF would be ideal. In such a blend, the RF would contribute to preventing the propagation of micro-cracks into meso-cracks, both IF and RF would contribute to preventing the propagation of meso-cracks into macro-cracks, and the IF would hold the macro-cracks together when they eventually appear. As a consequence, the concrete would be expected to resist a much higher number of cycles at higher stress levels.

It is important to note that these conclusions are based on results obtained mainly from RCC specimens subjected to the stress level of 0.7, hence, more work should be carried out to attest the above conclusions to other types of mix and stress levels.

It appears on Fig. 6b that CON–6RF mixes seem to sustain higher vertical displacements prior to failure than CON–2RF, however, this cannot be clearly deduced from the graph and hence, the influence of the fibre content on fatigue vertical displacement analysis should be further investigated. The influence of the mix type on the vertical displacement analysis also requires further investigation.

4.3. Probabilistic approach

This section aims to estimate the probability of failure (p_f) based on stress level and number of cycles. The probabilistic approach adopted is based on two different methods, one graphical and one mathematical, proposed by McCall [37] and slightly modified by Singh et al. [34,35]. This procedure is intended to be used to derive (for each mix) the family of S–N–p_f curves for design purposes.

4.3.1. Graphical method

For the graphical method, the mean (μ) and the standard deviation (σ) of the $\log(N_i)$ values for each stress level and each mix are

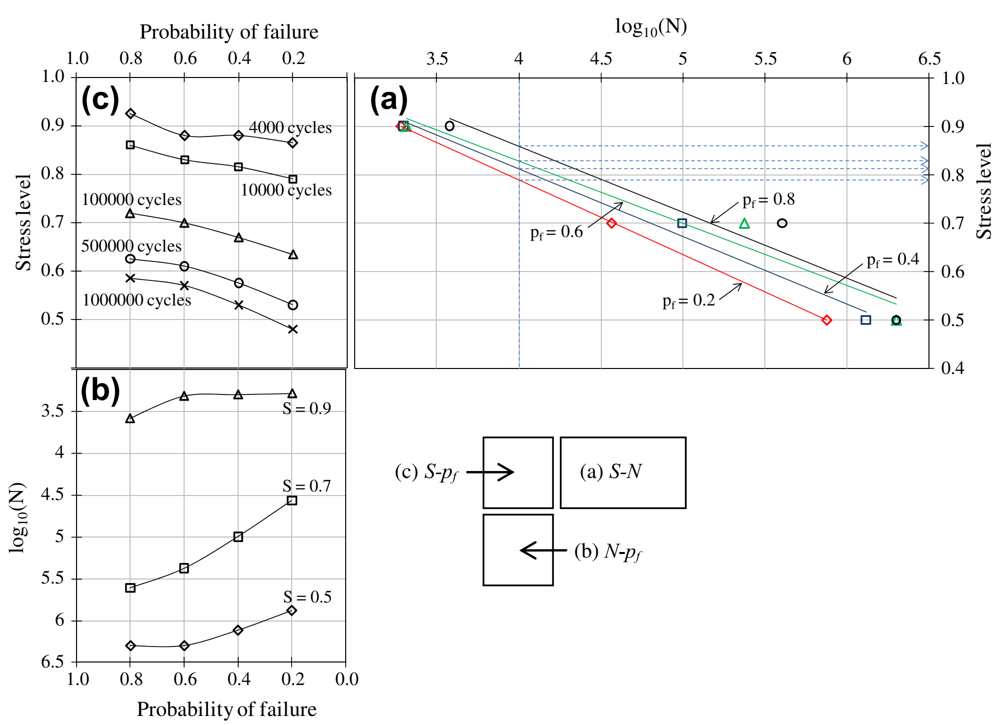

Fig. 12. Family of S–N–p_f curves of mix RCC-0 (graphical method).

initially calculated as shown for example in Table 5 for mix RCC-0 at the stress level of 0.5. All test series of different stress levels need to comprise the same number of specimens (in this study the minimum number is 4) and, hence, the Chauvenet's criterion of rejection was used to discard the additional specimens that deviate most from the mean (specimens with highest values of $|\log(N_i) - \mu|/\sigma$, see Table 5).

The specimens are then ranked according to the increasing number of cycles for each stress level. The p_f for each rank of specimens is calculated by dividing the rank of specimens i by $(n + 1)$, where n is the total number of specimens tested per stress level. The ratio $i/(n + 1)$ can be considered as the best estimate p_f for fatigue analysis [34,34]. Table 6 shows the ranked specimens from mix RCC-0 and their p_f.

The family of S–N curves for each p_f can now be obtained using the linear regression curves (one curve per stress level) as shown in Fig. 12a for mix RCC-0; the $N - p_f$ curves are also plotted (one per stress level, see Fig. 12b). The S–p_f family of curves is then obtained by graphical interpolation (see Fig. 12c), using values for a given number of cycles from the S–N regression curves, plotted on the S–N graph. This last step is illustrated in Fig. 12 (for 10,000 cycles, $\log(N) = 4$), which also shows the complete family of S–N–p_f curves for mix RCC-0. Different numbers of cycles can be chosen in the last step and the ones selected in this study were 4000, 10,000, 100,000, 500,000 and 1,000,000. Using the above procedure, the results in terms of S–p_f and S–N curves are shown in Figs. 13 and 14, for CON and RCC mixes, respectively.

4.3.2. Mathematical method

The mathematical method aims to arrive at a general equation for the p_f (Eq. (1)) [37] by utilising experimental results.

$$p_f = 1 - 10^{-aS^b \log N^c} \tag{1}$$

where a, b and c are experimental coefficients determined by procedures explained elsewhere [37,34,35].

The derived values of a, b and c for the mixes examined in this study are shown in Table 7. The results of the mathematical method are also plotted in Figs. 13 and 14 (using dashed lines), for comparison with the graphical method.

For most of the cases, the mathematical curves do not agree well with the results from the graphical interpolation method. This is mainly due to the low number of results for each stress level. Moreover, since the graphical method does not give better results than the mathematical method, the mathematical procedure is adopted in this study for design implication purposes since it is simpler than the graphical method.

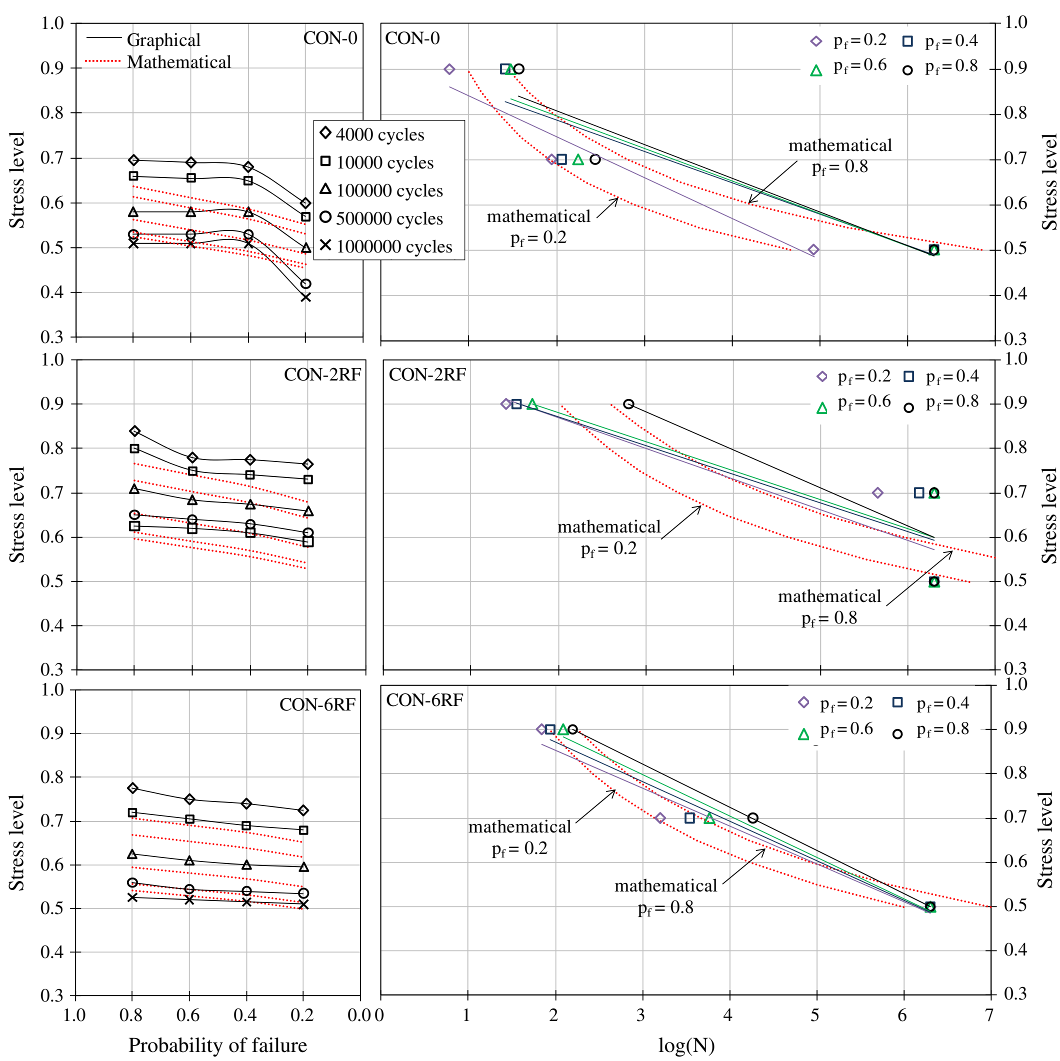

Fig. 13. Family of S–p_f and S–N curves of CON mixes (graphical and mathematical methods).

4.3.3. Acceptable levels of p_f in design

When dealing with fatigue of plain concrete, there is no universal consensus on the p_f to be used for design. For example, some studies [38,39] assumed values for p_f ranging from 1% to 10% and 5% to 50%, respectively, whilst others [40] including Eurocode-1 [41] limit the p_f of concrete structures subjected to fatigue to 5% and 7%, respectively. The limit of 5% is considered to be conservative [40]. Many authors proposed fatigue equations based on the probability of failure of 50% [42,32,43], which is considered unsafe [42].

Table 7
Experimental coefficients *a*, *b* and *c* calculated from the mathematical probabilistic method.

Mix	Experimental constants		
	a	*b*	*c*
CON-0	4.45E−1	13.7	5.15
CON−2RF	2.00E−3	16.1	7.90
CON−6RF	2.69E−4	24.8	12.9
RCC-0	1.01E−12	22.2	22.3
RCC−2IF	5.10E−3	4.49	3.96
RCC−2RF	1.27E−1	7.00	2.72
RCC−6RF	1.52E−7	16.3	12.9

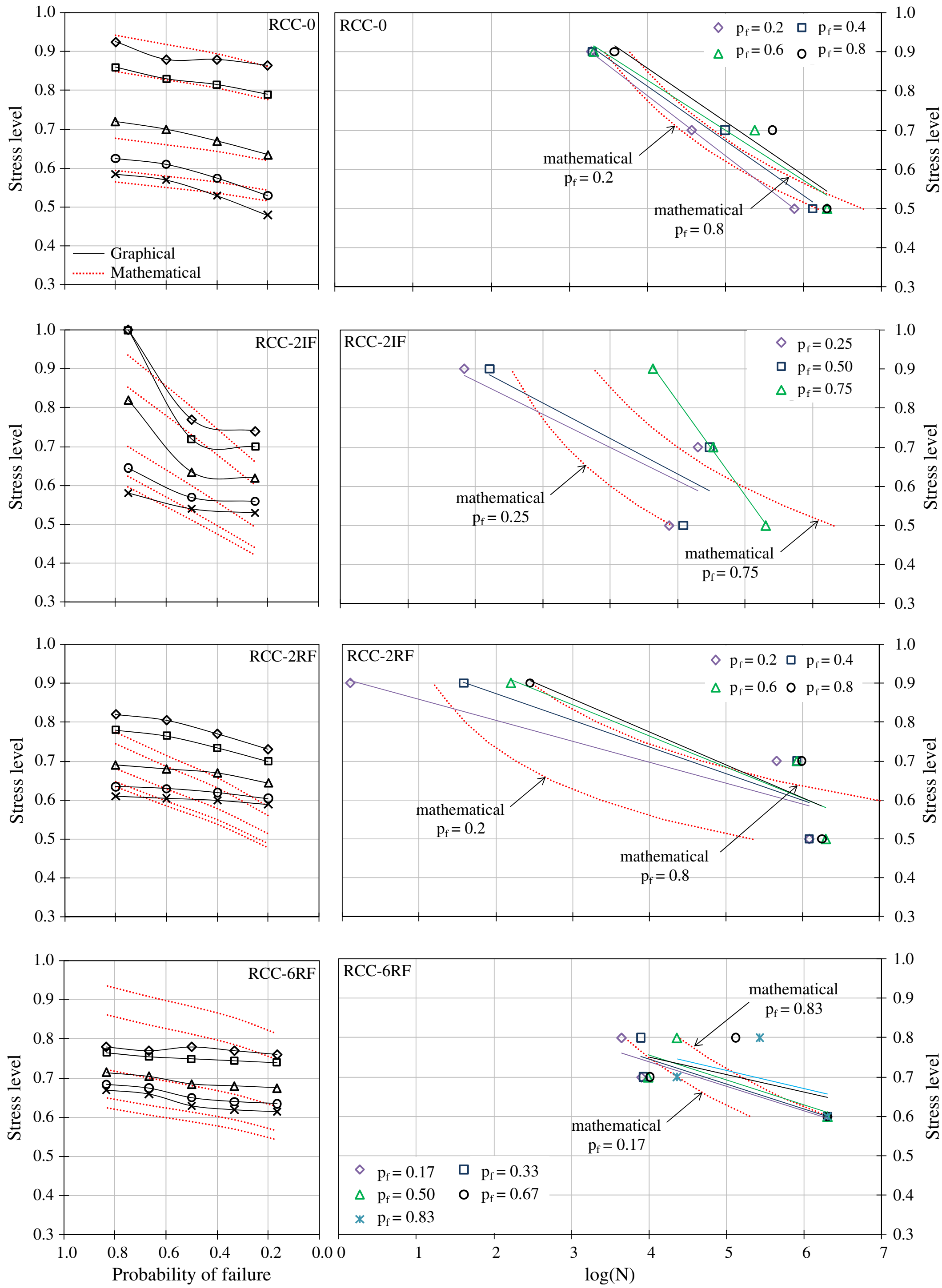

Fig. 14. Family of *S*–p_f and *S*–*N* curves of RCC mixes (graphical and mathematical methods).

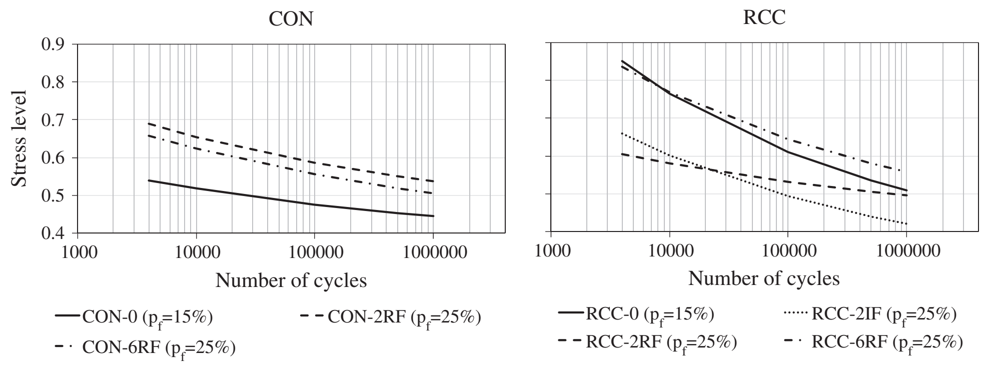

Fig. 15. Comparison of *S–N* curves based on a p_f of 15% (plain concrete) and 25% (reinforced concrete).

In the opinion of the authors, for plain concrete, values of p_f lower than 5% may lead to conservative fatigue design, whilst values above 20% may reduce the pavement's safety due to the variability of fatigue data. Nevertheless, higher values of p_f should be acceptable when dealing with SFRC due to the fact that fibres improve the structural performance of pavements as a result of stress redistribution. For the purpose of this study, a p_f of 15% was used for plain concrete whilst a p_f of 25% was used for fibre reinforced concrete [44]. Based on these p_f values, *S–N* curves were obtained for the seven concrete mixes as shown in Fig. 15. The curves were derived by using data from the mathematical method (Eq. (1), Table 7).

RCC-0 and RCC–6RF mixes show the best fatigue behaviour whilst CON-0 shows the lowest fatigue resistance in terms of p_f. As expected CON–2RF and CON–6RF mixes show a considerably better resistance to fatigue failure than CON-0 mix. Some RCC mixes investigated in this research (RCC-0 and RCC–6RF) have improved fatigue behaviour compared to the corresponding CON mixes, with the benefit of using lower cement content. For the same fibre content, RF show better performance than IF when subjected to stress levels below 0.57.

The main conceptual difference between the *S–N* curves shown in Section 4 and the probabilistic *S–N* comparison shown in this section is that material partial safety factors may not be required in design procedures for the probabilistic analysis if the limit p_f is correctly assumed.

5. Design implications of SFRC with recycled fibres in pavements subjected to fatigue

The fact that steel fibres improve the fatigue resistance of concrete should be taken into account in the design guidelines of concrete pavements. This could reduce the pavement thickness which, in conjunction with the environmental benefits of using recycled steel fibres, would lead to a more sustainable alternative for road construction, with less use of natural resources.

A simple example is given in this section aiming to quantify the likely reduction in the concrete pavement depth if the benefits of adding steel fibres in the concrete are taken into account in terms of fatigue resistance. For that, a road section located near Sheffield (UK) is taken into account for a design traffic of 314 msa (million standard axle), with a design thickness of 300 mm [45]. A concrete with compressive strength of 55 MPa, flexural strength of 6.5 MPa and modulus of elasticity of 30 GPa is considered in this example. These values are similar to RCC–2RF concrete. According to Westergaard equations [46], the maximum stress level for the road section should be around 0.26 at the corner of a pavement plate.

If the probabilistic analysis based on the mathematical method is taken into account, the stress level for an endurance life of 2 million cycles and p_f of 25%, is equal to 0.49, for the RCC–2R mix. If this new stress level is used to recalculate the concrete depth considering the Westergaard equations [46], the concrete depth would reduce by approximately 26%. However, it is important to note that this calculation does not show the true benefits of using SFRC over plain concrete, since this reduction does not take into account other effects, such as environmental deterioration and other failure mechanisms (e.g. roughness degradation), but uses fatigue as the only failure mechanism.

Another factor that must be taken into account is that the fatigue behaviour of concrete beams is different to that of concrete slabs in real pavements [43]. Slabs are reported to be approximately 30% stronger than beams, which can lead to an underestimation of the fatigue performance of the concrete when using results from fatigue of concrete beams. This aspect was not evaluated in this paper, but should be taken into account when dealing with design implications for fatigue of SFRC pavements.

6. Conclusions

The use of recycled steel fibres recovered from post-consumer tyres as fatigue reinforcement for concrete pavements was investigated in this study by means of an experimental programme in which concrete prisms were subjected to cyclic flexural loads. The main findings of this study are outlined below.

- Specimens reinforced with recycled fibres can sustain higher stress levels than plain concrete or, for the same stress level, they have longer endurance life. This is especially true for conventional concrete mixes, whilst for roller compacted mixes, this is correct for stress levels lower than 0.7.
- 2% by mass of concrete seems to be an ideal recycled fibre content that gives the best fatigue performance.
- RF are efficient in restraining the propagation of micro-cracks into meso-cracks whilst IF are more efficient in holding macro-cracks together. Hence, a combination of both recycled and industrially produced fibres appears to be ideal in terms of increasing the fatigue endurance life.
- Fibre reinforced RCC with RF shows similar behaviour as fibre reinforced CON, but with the advantage of using 25% lower cement content and a faster construction process. Plain RCC has a considerably higher fatigue resistance the plain CON, due to aggregate interlock.
- A probabilistic approach can be used in practice for design purposes, along with the proposed probabilities of failure of 15% for plain concrete and 25% for SFRC.
- The fact that fibres contribute to improve the fatigue performance of concrete may lead to a reduction of up to 26% in the pavement thickness. This information should be used along other failure mechanism criteria in the design codes of concrete pavements.

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