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An overview of the fatigue behaviour of plain and fibre reinforced concrete

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Abstract

The paper provides a general overview of recent developments in the study of the fatigue behaviour of plain and fibre reinforced concrete (FRC). The fatigue performance of plain concrete and FRC, as reported in the literature, is compared in order to quantify the influence of fibre inclusion on fatigue behaviour. Despite the conflicting information regarding the fatigue behaviour of concrete reported in the literature, the majority of researchers show that the inclusion of fibres can benefit the fatigue performance of concrete.

Keywords: Fatique behaviour; Concrete; FRC; Structures

1. Introduction

The paper provides a general review of recent developments in the study of the fatigue behaviour of plain and fibre reinforced concrete (FRC). Many structures are often subject to repetitive cyclic loads. Examples of such cyclic loads include machine vibration, sea waves, wind action and automobile traffic. The exposure to repeated loading results in a steady decrease in the stiffness of the structure, which may eventually lead to fatigue failure. Although concrete is a widely used construction material, the understanding of fatigue failure in cementitious composites is still lacking in comparison to that of ferrous materials. This incomplete understanding is even more pronounced for composite materials such as FRC.

2. General background

Fatigue may be defined as a process of progressive, permanent internal structural changes in a material subjected to repeated loading. In concrete, these changes are mainly associated with the progressive growth of internal microcracks, which results in a significant increase of irrecoverable strain. At the macrolevel, this will manifest itself as changes in the material's mechanical properties.

Fatigue loading is usually divided into two categories [1] i.e. low-cycle and high-cycle loading. Low-cycle loading involves the application of a few load cycles at high stress levels. On the other hand, high cyclic loading is characterised by a large number of cycles at lower stress levels. Hsu presents a wider range of fatigue load spectrum with the inclusion of super-high cycle loading [2]. Table 1 summarises the different classes of fatigue loading.

As in the case of static tests, different loading arrangements have been used in fatigue testing, including compression, tension and bending tests. The most common method of fatigue testing, by far, is via flexural tests. To a lesser extent, compressive fatigue tests have also been investigated. In recent years, there has been more interest in the fatigue characteristics of concrete in tension [3–5], especially since the introduction of nonlinear fracture mechanics in the analysis of concrete. In addition, some researchers have studied the effects of combined stresses to the fatigue performance of concrete [6,7] where it has been found that the fatigue strength of concrete in biaxial compression is greater than that under uniaxial compression.

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Table 1
Classes of fatigue load, after [2]

Low-cycle fatigue			High-cycle fatigue				Super-high-cycle fatigue		
1	10^1	10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9
Structures subjected to earthquakes			Airport pavements and bridges		Highway and railway bridges, highway pavements		Mass rapid transit structure		Sea structures

Various approaches have been used in the fatigue life assessment of structural elements. A widely accepted approach for engineering practice is based on empirically derived *S–N* diagrams, also known as Whöler curves. In addition, the effects of minimum stress in the loading cycle may be represented in so-called Goodman diagrams or Smith diagrams, which are also known as constant life diagrams in the analyses of metals [8]. These empirical curves give a graphical representation of the fatigue performance for certain loading parameters. Another method is based on fracture mechanics concepts and has been incorporated in a finite element approach [9,10]. This method is more demanding but provides an insight into the underlying physical behaviour.

3. Fatigue of plain concrete

Concrete is a heterogeneous material which is inherently full of flaws (such as pores, air voids, lenses of bleed water under coarse aggregates and shrinkage cracks). The mechanism of fatigue failure in concrete or mortar can be divided into three distinct stages [11]. The first stage involves the weak regions within the concrete or mortar and is termed flaw initiation. The second stage is characterised by slow and progressive growth of the inherent flaws to a critical size and is generally known as microcracking. In the final stage, when a sufficient number of unstable cracks have formed, a continuous or macrocrack will develop, eventually leading to failure. Fatigue crack growth can be divided into two distinct stages [12]; the first stage is a deceleration stage, where the rate of crack growth decreases as the crack grows and the second stage is an acceleration stage, where there is a steady increase in the crack growth rate right up to failure [13].

It has been surmised that different loading cycle regimes produce different failure mechanisms within concrete. For low-cycle fatigue, the dominant mechanism is the formation of mortar cracks leading to continuous cracked networks. On the other hand, high-cycle fatigue produces bond cracks in a slow and gradual process [14].

Unlike ferrous metals, concrete does not appear to have a fatigue limit. It has been reported that plain concrete subjected to repeated uniaxial tensile stresses exhibits no fatigue limit under 2×10^6 cycles [15]. Hence there is no known stress level below which the fatigue life of plain concrete will be infinite.

In general, parameters such as loading conditions, load frequency, boundary conditions, stress level, number of cycles, matrix composition, stress ratio will influence the fatigue performance of the concrete specimen. However, the qualitative and quantitative nature of these parameters on the fatigue performance of concrete is yet to be agreed in the literature.

4. Fatigue of fibre reinforced concrete

The use of FRC in engineering applications has furthered the need for the study of its behaviour under fatigue loading. Common applications for FRC include paving applications such as in airports, highways, bridge decks and industrial floors [16], which endure significant cyclic loading during their service life. Within these areas of application, the fatigue characteristics of FRC are important performance and design parameters. However, there seems to be a gulf in the knowledge of the fatigue behaviour of FRC in terms of all the influencing variables such as type of loading cycle, strain rates and fibre parameters.

Generally, it has been observed that the addition of steel fibres can significantly improve the bending fatigue performance of concrete members [17–19]. The extent of improvement on the fatigue capacity of FRC can be expected to depend upon the fibre volume content, fibre type and geometry. Various combinations of these parameters will give rise to different fatigue characteristics. However, at the moment, there does not seem to be a comprehensive appreciation of the advantages than can be attained with fibre addition, as there is limited information regarding the quantitative influence and relative importance of fibre parameters such as amount, aspect ratio and fibre type. In general, the addition of fibres has added a further dimension to the study of fatigue in concrete and has increased the complexity of analysis.

As stated previously, the development of fatigue failure in concrete can be divided into three stages. It is feasible to retard and inhibit the growth of the flaws in the second stage by introducing closely spaced and randomly dispersed fibres as reinforcements. In FRC, the action of fibre bridging and fibre pullout dissipates energy in the wake of the crack tip. This mechanism plays a dominant role in inhibiting crack growth and therefore increases the load carrying capacity of FRC specimens.

It is hoped that the addition of fibres will endow the FRC with a fatigue limit, thus making it a much more attractive material than plain concrete, which appears to have no such limit [2]. Li and Matsumoto [20], through their model, showed that a fatigue limit exists for FRC. Ramakrishnan and Lokvik [21] suggests that FRC reaches an endurance limit at approximately 2×10^6 loading cycles. However, it has been proposed that tests up to 10×10^6 cycles need to be carried out to confirm this conclusion [17]. From the numerous reported findings, it is obvious that the question of whether FRC has a fatigue limit remains unresolved.

The addition of steel fibres has been found to substantially improve load-bearing capacity and resistance to crack growth [22]. As in the case of static loading, fibres have been found to result in the development of a large number of small cracks rather than a small number of large cracks [18]. Furthermore, the inclusion of fibres produces a more ductile behaviour during fatigue loading [23,24].

A significantly higher level of damage in static as well as fatigue testing of SFRC has been found compared to that observed in plain concrete [19]. This is further supported by findings reported in [25] where it is concluded that FRC could undergo larger strains before failure, compared to plain concrete.

The addition of fibre reinforcement has been found to have a dual effect on the cyclic behaviour of concrete. Fibres are able to bridge microcracks and retard their growth, thereby enhancing the composite's performance under cyclic loading. On the other hand, the presence of fibres increases the pore and initial microcrack density, resulting in strength decrease. The overall outcome of these two competing effects depends significantly on the fibre volume [18].

It has been suggested that the presence of fibres only help to enhance the composite behaviour in fatigue in the low cycle region (up to approximately 10^3 cycles) [7]. Fibres are not seen to provide any improvement for higher number of cycles. This is elucidated by the differentiation between mortar and bond cracking [14]. The presence of fibres is able to increase the fatigue life in the part of mortar cracking (low cycle region), but is unable to do so when bond cracking (high cycle region) starts. Consequently, the addition of fibres is deemed to be unable to increase the fatigue limit (if such a thing exist) of concrete. Paskova and Meyer [26] suggest that fibres tend to dissipate more energy at lower stress levels compared to higher stress levels.

Most researchers agree that FRC has better fatigue behaviour compared to plain concrete. However, there is conflicting evidence based on the work of Cachim [27]. For uniaxial compression, 30 mm fibres increased fatigue life while 60 mm fibres actually reduces it. On the other hand, for flexural fatigue tests, it appears that only a marginal benefit comes from fibre addition. To explain these observations, it was concluded that the additional flaws introduced by fibre addition outweighed the benefits for some of the tests carried out.

The main benefit of the addition of fibres in the concrete matrix is the increased ability to absorb energy. Increasing the fibre content and aspect ratio increases the amount of energy spent on crack growth of SFRC under fatigue load [28]. The main fibre parameter influencing the fatigue performance of FRC seems to be the fibre content. On the other hand, the aspect ratio and fibre type is secondary in importance [17,29].

5. Comparison using results from literature

The majority of fatigue life prediction and design of plain and FRC structures have been carried out empirically. This method involves time consuming testing for a broad range of design cases, which in principle may be inapplicable to other design cases.

To date, there is no standard procedure for carrying out fatigue tests on concrete or FRC. Strictly speaking, fatigue data obtained from a particular test set-up cannot be directly compared to data obtained from different loading configurations [13]. However, *S–N* curves are plotted using strength (or stress) values, which are made dimensionless by relating them to the static strength. The dimensionless term, *S*, in part eliminate influences such as specimen shape, water–cement ratio, type and grading of aggregates, concrete strength, curing condition, moisture conditions and age at loading etc. Dimensionless *S–N* curves are thought to represent as close as possible the true behaviour of concrete under fatigue loading [14].

There is no agreement whether *S–N* curves may be used for all types of specimens, loading configurations, testing conditions etc. However, by plotting some of the available data in the literature, it is hoped that some general trends may be identified. More specifically, it would be interesting to see whether the fatigue data would be able to show the qualitative benefits of fibre addition. Nevertheless, it must be kept in mind that, due to differences in the test programmes, a direct relationship cannot be made and this approach only provides a general comparison.

Various researchers have carried out compressive fatigue tests on plain concrete and SFRC [18,26,27,30]. Similarly, flexural fatigue tests on plain concrete and SFRC have been extensively studied [17,27,28,31–36]. For the purpose of the comparison carried out in this review, only work carried out using steel fibres with fibre

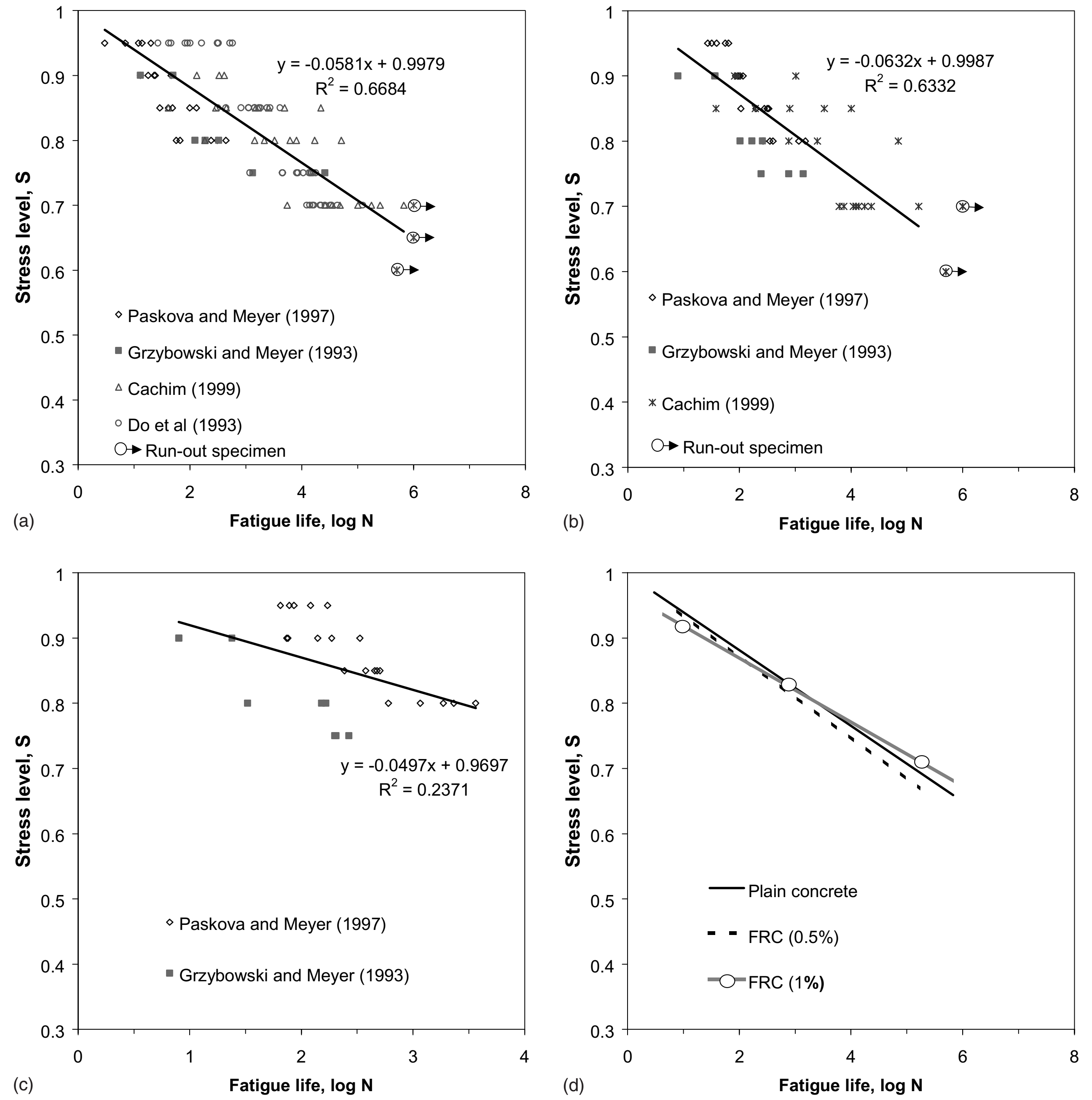

Fig. 1. (a) *S–N* curve for plain concrete under compression; (b) *S–N* curve for SFRC (0.5% fibre content) under compression; (c) *S–N* curve for SFRC (1.0% fibre content) under compression. (N.B. Change of scale for log *N*); (d) comparison between *S–N* curves for plain and SFRC (0.5% and 1.0% fibre content) under compression.

concentrations (by volume) of 0.5% and 1.0% have been considered.

Fig. 1(a) shows the *S–N* curve obtained from an analysis by the authors on the test results extracted from the literature [18,26,27,30] for plain concrete in compression. On the other hand, Fig. 1(b) and (c) present the *S–N* curves for SFRC containing 0.5% and 1.0% of fibres under compression fatigue loading respectively. Fatigue test results in the literature shows significant spread in the results and care is required in the interpretation of the trendlines shown in Fig. 1 since the coefficient of determination, R^2, is significantly less than unity. For a more meaningful comparison, Fig. 1(d) shows the linear regression lines for the results shown separately in the previous three figures. There appears to be a slight degradation in the fatigue life of SFRC relative to plain concrete under compression loading. A similar trend has been reported in [27] for only one test series. This was attributed to the introduction of additional flaws within the concrete matrix by the fibres.

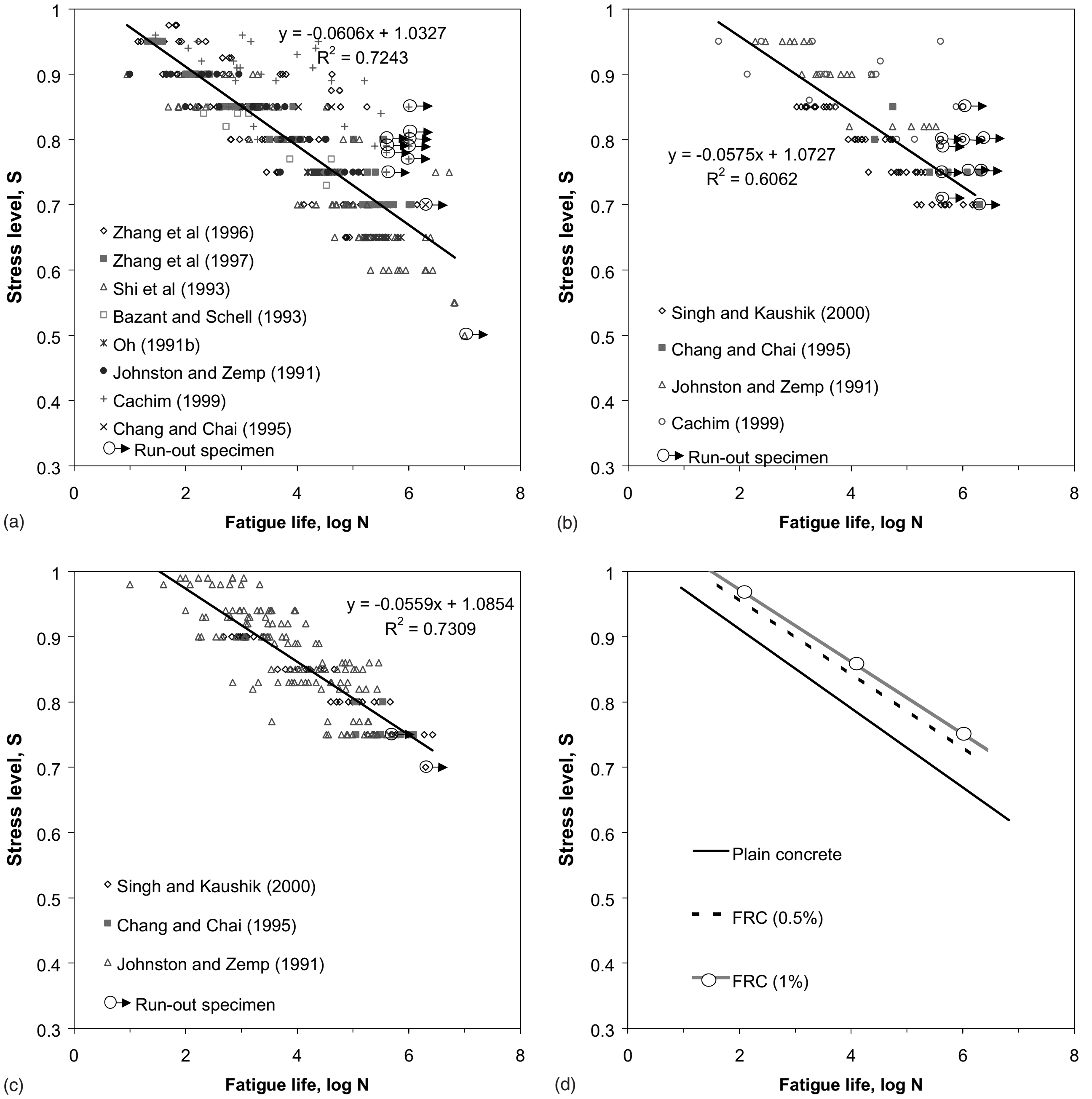

Fig. 2. (a) *S–N* curve for plain concrete under flexural loading; (b) *S–N* curve for SFRC (0.5% fibre content) under flexural loading; (c) *S–N* curve for SFRC (1.0% fibre content) under flexural loading; (d) comparison between *S–N* curves for plain and SFRC (0.5% and 1.0% fibre content) under flexural loading.

Fig. 2(a) presents the *S–N* curve for plain concrete under flexural loading. Similarly, Fig. 2(b) and (c) give the *S–N* curves for SFRC containing 0.5% and 1.0% of fibres under flexural loading respectively. Similarly the R^2 values are significantly less than unity for these test results but are slightly better than those observed for the compression test results. Finally, Fig. 2(d) compares the linear regression lines for all three test results in flexure. Contrary to the observations for compressive fatigue loading, there appears to be a significant benefit derived from the addition of fibres. The improvement is slightly greater when the fibre content is increased from 0% to 0.5% compared to the improvement achieved between 0.5% and 1.0%. A comparison between the contradictory trends between SFRC under compressive and flexural fatigue loading suggests that SFRC is more effective under the latter conditions. This is to be expected, since the fibres would be able to bridge cracks and prolong fatigue life. The presence of fibres cannot display their true effectiveness under compressive loading, as the mode of failure does not induce a significant contribution from the fibres.

Due to the variety of testing configurations, materials and procedures, the conclusions given above are only tentative. However, due to the numerous sources of fatigue data analysed, most systematic variations should have been removed in compiling the various test results. Hence, the qualitative trends observed should be generally applicable.

6. Conclusions

There is a significant amount of conflicting information in the literature regarding the fatigue behaviour of cementitious materials. Even for the case of plain concrete, many contradicting trends have been reported. Therefore, it is hardly surprising that there does not seem to be a general consensus about the effects of fibre inclusion on the fatigue life of concrete. The inclusion of fibres has added a further dimension to the understanding of the fatigue of concrete. Even when considering fibre parameters alone, there are numerous combinations which can influence the fatigue behaviour of FRC. In addition, there are various combinations of loading frequency, load sequencing, matrix composition, test configuration etc. which can be expected to change the behaviour of FRC under cyclical loads.

Nevertheless, the majority of researchers have, to a limited extent, found that the inclusion of fibres can benefit the fatigue performance of concrete. However, the quantitative nature of this benefit is difficult to determine. The results analysed in this paper would suggest that an endurance limit (if such exist) has not been observed before 10^6 cycles. Further experimental work beyond 10^6 cycles is required before drawing firm conclusions regarding an endurance limit.

The lack of a well-established test procedure for executing and evaluating fatigue tests makes it difficult to correlate or extend published test results. However, a compilation of fatigue data from numerous sources has been carried out to observe general trends from which tentative conclusion have been drawn. The presence of fibres does not seem to enhance the fatigue life of concrete under compressive fatigue loading. On the other hand, fibre addition benefits the fatigue performance under flexural fatigue loading. A possible explanation is that under tensile forces, the fibres are able to bridge cracks and prolong fatigue life. On the contrary, the presence of fibres cannot display their true effectiveness under compressive loading, as the mode of failure is different.

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