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A Review on Fatigue Performance of Concrete Structures Part II, Material Parameters and Environmental Factors

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ABSTRACT

Fatigue is a critical issue for concrete structures subjected to repetitive and varying loads, particularly in infrastructure and transportation systems. This review paper presents a comprehensive overview of the current state of knowledge on concrete fatigue and identifies areas for further research. Material and size factors that influence fatigue performance and life estimation of concrete such as concrete composition, internal moisture content and reinforcement are explored, along with environmental conditions such as presence of external moisture and seawater exposure. The paper also acknowledges the challenges associated with predicting concrete fatigue life accurately due to the heterogeneous nature of concrete and its complex behavior under cyclic loading.

Key words: review, fatigue of concrete, reinforced concrete, material level, environmental condition

1 INTRODUCTION

Concrete is a highly popular construction material because of its capability to endure various environmental and loading circumstances. Nevertheless, concrete structures face a variety of static and dynamic loads, which may result in the deterioration of the material. A complex phenomenon that leads to failure of concrete is fatigue, which may happen due to repeated loading and unloading cycles. This can lead to cracking, spalling, and other forms of damage [1-4]. In contrast to isotropic materials, the fatigue capacity of concrete structures exhibits a higher level of complexity due to its non-homogeneous nature. Unlike materials with uniform properties, concrete's fatigue behavior is influenced by a multitude of factors beyond loading parameters. Fatigue performance of concrete is influenced by various material parameters and environmental conditions, such as its composition, moisture content, presence of reinforcement, seawater exposure, temperature, etc. Understanding how these parameters affect the fatigue life of concrete is essential for designing and constructing durable, long-lasting structures.

The study of concrete structures' fatigue performance has gained significant attention in recent years, especially in regards to infrastructure that is exposed to harsh conditions and dynamic loading such as offshore wind turbines. Viswanath et al. [5] investigated fatigue testing on cylindrical concrete specimens intended for wind turbine foundations and highlighted the necessity for improved fatigue design guidelines to enhance the accuracy of predictive models. Many research endeavours have focused on examining how various material parameters impact concrete structures' fatigue life [1, 6-9]. These studies have used different approaches, such as experimental testing, theoretical modeling, and numerical simulation. Despite the intensive research, there remains a lack of reliable design methods for fatigue analysis and assessment of concrete structures. The complex behavior of concrete structures under cyclic loading and the absence of consistent testing methods have contributed to this problem. As a result, accurately predicting and managing fatigue failure in concrete structures remains a challenge for the industry. It is therefore important to continue exploring and developing new design methods and testing techniques to improve the reliability of concrete structures and ensure their safe and efficient operation.

In order to facilitate the organization and correlation of various factors related to fatigue of concrete structures, the review has been divided into two separate papers. The primary focus of the first part is to examine the impact of loading parameters on the fatigue behavior of concrete structures, explore different methodologies for estimating fatigue life, and discuss design approaches [10]. Whereas, the second part (this paper) aims to provide a comprehensive overview of the literature on the material parameters affecting the fatigue performance of concrete structures. The paper will discuss the mechanisms of fatigue in concrete structures, the experimental methods used to measure fatigue, and the various material parameters that have been shown to influence fatigue life. The paper will also highlight the challenges and limitations of the current research on fatigue in concrete structures and suggest areas for future research.

2 MATERIAL PARAMETERS AND ENVIRONMENTAL FACTORS

2.1 Concrete composition

It is generally believed that the composition of concrete plays a vital role in failure mechanism and strength characterization [11], thus, concrete composition is a great influential factor in fatigue behavior when referred to the ratio of static strength. Concrete is a heterogeneous type of material having different stiffnesses in different zones. Since a large amount of cracking mainly develop along the cement aggregate interface [12], the different stiffness in the interface zone, between aggregate and cement paste, is of great importance when it comes to fatigue capacity. Breitenbücher et al. [13] showed that enhanced stiffness of aggregates resulted in more severe cracks in this zone. As an example, the sandstone with a stiffness closer to cement paste (≈20 GPa), creates a more uniform stiffness throughout the specimen resulting in less crack growth and consequently higher lifespan within the fatigue life period. In another study, Scheiden and Oneschkow [14] tested fatigue properties of high-strength concrete (HSC) with the same composition and testing procedure but with two different aggregate types of basalt and granite. In spite of achieving almost the same compressive strength, basalt composition showed a higher fatigue strength for S_{max} = 0.7, but at the higher maximum stress level (S_{max} = 0.85) it was granite composition that showed higher fatigue strength. The acoustical emission test, which can be used as a damage indicator as a result of energy dissipation, served as supporting evidence for their findings. Although they did not propose an explanation for this discrepancy, they found that the aggregate composition might change the damage mechanism based on analyzing the strain and acoustical emissions data from the samples.

Saini and Singh [15] conducted flexural fatigue strength tests on self-compacting concrete using mixed cements and recycled concrete aggregates. The fatigue tests were carried out at stress levels ranging from 0.95 to 0.65. The frequency of the tests was set at 10 Hz, utilizing a sinusoidal waveform. Their findings indicated that the concrete containing approximately 50% recycled aggregate by the total aggregate volume exhibited a decreased fatigue life compared to concrete with normal aggregates. They attributed this primarily to the inferior properties of recycled aggregate concrete, which can be attributed to the presence of adhered mortar surrounding the aggregates. This presence of adhered mortar led to micro defects within the concrete, resulting from cracks and fissures, as well as a weak interfacial transition zone between the new mortar and recycled aggregate. Additionally, the inclusion of recycled aggregate led to a reduction in compressive and flexural strength. However, Saini and Singh noted that the lower fatigue life, as well as the decrease in compressive and flexural strength, could be mitigated by incorporating cement with metakaolin and silica fume. In a similar research context focusing on the incorporation of mineral additives in concrete, Golewski [16] investigated the impact of fly ash (FA) addition at different proportions of 20% and 30% of the total binder on the fracture toughness of concrete. The findings revealed that the addition of 20% FA yielded the most favorable outcomes, resulting in higher mechanical parameters and improved fracture toughness of the material. Sun et al. [17] investigated the influence of FA on the fatigue performance of roller compacted concrete. Despite the escalation of fatigue damage as the FA content rises from 0% to 45%, the addition of FA leads to an increase in fatigue strength. The authors propose that the primary factor behind this observation is the consistent enhancement of ultimate flexural strength as the FA content increases. Furthermore, FA has the ability to react with calcium hydroxide, a hydration product of cement, thereby reducing its quantity. This reaction promotes the formation of more CSH gel (calcium silicate hydrate) and Aft (ettringite), leading to an improved pore structure and a denser matrix.

Baktheer and Chudoba [18] proposed an additional dissipative mechanism for HSC due to crack propagation through the aggregate in addition to the dissipative effect of plastic deformation through plastic sliding along the aggregate interface. There might be other reasons for the formation of microcracks in the interface zone due to the cyclic loading. One reason for the reduction in strength of the interface zone is based on the chemical composition found in this area. A thin layer of $Ca(OH)_2$ covered the aggregate surface and followed by a layer of 50 µm thick hydrated cement particle and larger $Ca(OH)_2$ crystal. Since there is no trace of unhydrated cement in this layer, it indicates a higher water-cement ratio than elsewhere [11, 19], resulting in a weaker strength. Other reason might be the "Wall Effect" [11], where the cement is not completely packed around the aggregates, consequently, the empty voids may cause the formation of larger $Ca(OH)_2$ and as a result, the transition zone become more porous, which reduces the strength. Gan et al. [20] conducted a study focusing on the interfacial transition zone (ITZ) at a micrometer length scale to investigate its flexural strength and fatigue properties. To analyze the ITZ, they attached a hardened cement paste cantilever to a quartzite aggregate surface. Cyclic loading was applied at a constant amplitude and a frequency of 0.55 Hz. The maximum stress level ranged from 60% to 90% of the static flexural strength. The authors [20] examined the ITZ using backscattered electron images and energy dispersive spectrometer analysis. They found that the mechanical properties of the ITZ, particularly its strength, were approximately 44-50% of the bulk cement paste at a similar length scale. This resulted in a lower fatigue resistance for the ITZ. The authors observed that the critical crack primarily formed along the edge of the aggregate, with only a small portion penetrating into the ITZ. This failure mode was attributed to the weak bond between hydration products and the aggregate [20].

The relationship between the composition of concrete and its fatigue capacity is a complex and multifaceted subject. Through the literature review conducted in this paper, although the fatigue strength of concrete is impacted by various factors in grading and composition scale, it is also important to consider the curing conditions. The curing process can affect the strength and durability of concrete, and thus can impact its fatigue capacity.

2.2 Moisture content

Water is among the most fundamental components of concrete that is always present naturally in concrete with different content. As shown in Figure 1, the study of the static strength of concrete has found a well-established relation between the water-cement ratio and its effect on concrete strength.

The effect of natural moisture content and the presence of external moisture/water on fatigue performance, beyond their effect on static strength, has been investigated [8, 21-27]. All referred studies were in agreement that the drier the sample, the higher the fatigue strength would be.

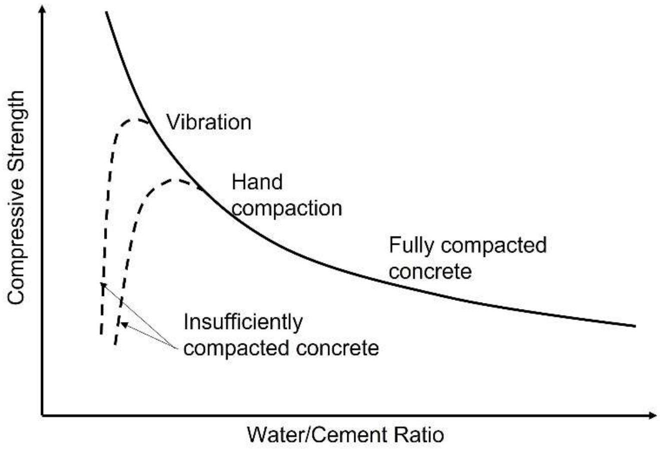

Figure 1 - Relation between compressive strength and w/c [11].

Seitl et al. [21] conducted a study on the impact of water-to-cement ratio on the fatigue behavior of concrete. The authors performed bending tests on samples with three different water-to-cement ratios: 0.3, 0.4, and 0.5. To prevent water exchange with the environment, the sample blocks were sealed after casting and 24 hours of curing, ensuring consistent internal moisture content during the tests. The results revealed a clear correlation between water-to-cement ratio and fatigue life. Decreasing the water-to-cement ratio resulted in an increase in fatigue life, with a 10% improvement in fatigue resistance (measured by bending stress amplitude) for a same number of loading cycles when the ratio decreased from 0.5 to 0.3. The findings of Shah et al. [22] were consistent with the results.

In one of the early studies, Galloway and Raithby [23] investigated the effect of moisture content on plain concrete beams subjected to bending. All specimens with the same composition (*w/c* = 0.5) were initially cured in water until they were implemented in four different test regimes (Table 1). The results are shown in Figure 2. Galloway and Raithby found that the oven-dried samples endured the most cycles and concluded that the moisture gradient is of greater importance than the amount of moisture content, as the differential strains induced by the moisture gradient.

Table 1 - Moisture state by Galloway and Raithby [23]

Moisture states	Description of state
1	Specimens saturated throughout testing
2	Specimens allowed to dry for one week at 20°C and 65% *RH*
3	Specimens oven-dried for one week at 105°C
4	Specimens over-dried for one week at 105°C, then resoaked for 3 weeks

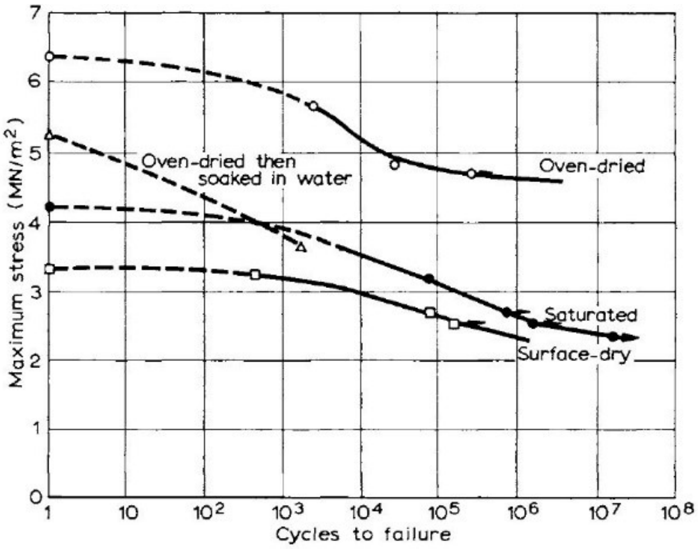

Figure 2 - Moisture influence on fatigue life [23].

In a recent study, Tomann and Oneschkow [8] concluded that the natural water in the concrete micro-structure is the main contributor to strength reduction compared to external water, which is a minor contributor. They exposed cylindrical (size: *h/d* = 300/100 mm) HSC specimens with *w/c* ratio of 0.35 to a sinusoidal compression loading with different moisture states shown in Table 2. The dynamic Young's modulus, which is a description for a deformation resistance against an impact load, increased with increasing moisture content. Winkler [28] explained this phenomenon by increasing the moisture content of the pore structure, which led to higher stiffness of the concrete. Besides, as shown in Table 2, the result showed that the moisture content slightly influenced the compressive strength. In terms of fatigue endurance, Figure 3 illustrates that the moisture state (C) corresponds well with *fib* Model Code 2010 [29], and *DNV* [30] seems to be more conservative in fatigue prediction. Moreover, the effect of moisture content is significant when comparing the dried specimens with the others. The dried specimens endured around 10^7 cycles without failing, while the rest failed below 10^6 cycles. Mor et al. [27] suggested that an increase in moisture content leads to porewater pressure, which then adds tensile stresses to the microstructures. In addition, the effect of water-pumping phenomenon between pores during cyclic loading (opening/closing cracks) can lead to further degradation. An acoustic emission test was performed in their work to substantiate the hypothesis of damage effect. The specimens with higher moisture content showed more acoustical emissions per cycle, which indicates a higher progressive deterioration [8].

Table 2 - Stage condition and material properties at the age of 90-days [8]

Stage condition	Moisture content mass %	Dynamic Young's modulus (GPa)	Compressive strength (MPa)
(D) Dried-105±5*℃*	≈0	41.7	108
(C) Climate chamber 20℃,65% *RH*	3.5	47.1	97
(M) Sealed	4.3	52.4	107
(WS) Water stored	5.0	53.3	110
(WST) Water stored, tested in water	5.0	53.3	110

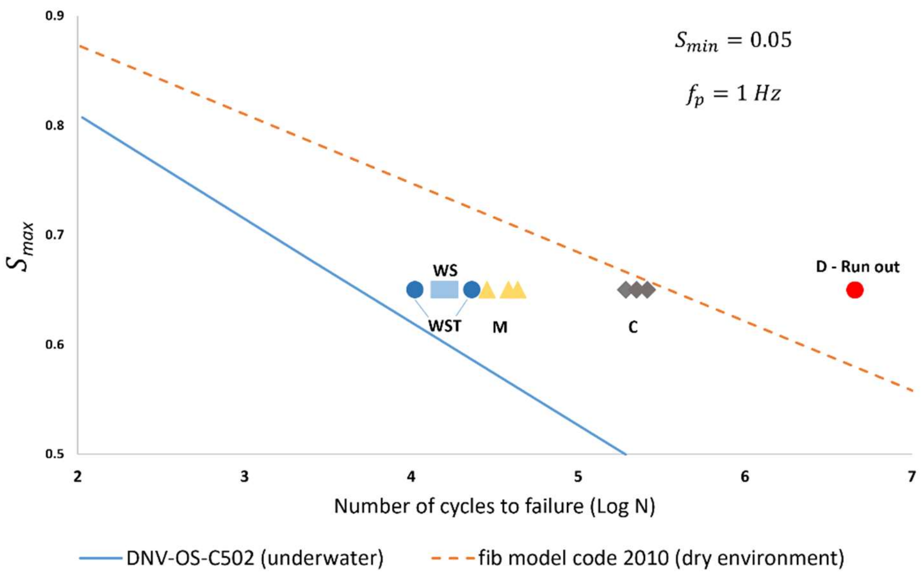

Figure 3 - Effect of storage condition on number of cycles to failure [8].

In another study, Petkovic [25] performed a test on the effect of moisture in different-size cylindrical specimens. Three sizes of cylinders (Ø50, Ø100, Ø450) and three different moisture stages (air, sealed, water) were included in the test. He concluded that the excessive moisture content decreases fatigue life, in addition, the evaporation of water only occurs at the outer layers, meaning that the moisture effect is scale-dependent, and consequently, larger specimens are less affected by air/sealed condition.

To sum this part up, the presence of moisture and water in concrete has a significant effect on its fatigue performance, in addition to its static strength. While existing literature offers valuable insights into the effect of moisture and water content on the fatigue performance and strength of concrete, there are some limitations to consider. Firstly, these studies were conducted on a limited number of samples and under specific experimental conditions, which may not fully represent the variability and complexity of real-world situations. Therefore, the results may not be generalized to all types of concrete and environmental conditions. Secondly, the literature mainly focuses on the impact of moisture on fatigue performance and strength, but it does not consider other factors that may affect concrete properties, such as temperature, chemical exposure, and loading type. Lastly, the literature does not provide practical recommendations on how to control the moisture content in concrete to improve its durability.

2.3 Seawater

In recent years, there has been high investment in the transit to clean and renewable energies, and there seems to be a great potential for offshore wind turbines. Therefore, the issue of concrete durability in seawater and its relation to fatigue has received significant attention. One of the critical challenges faced by concrete structures, particularly those in marine environments, is the deleterious effect of chemical reactions and chloride ingression. The combination of fatigue loading and deleterious effect from seawater poses significant challenges to the long-term performance of concrete structures. Understanding and addressing these issues are crucial for ensuring the durability and reliability of offshore structures.

The reaction of magnesium sulphate ($MgSO_4$) that seawater is rich in with calcium hydroxide ($Ca(OH)_2$) forms magnesium hydroxide, which acts as a temporary protective layer at the surface of the concrete, and concrete is further degraded as seawater erodes this layer, see Equation 1 [11]:

$$M_gSO_4 + Ca(OH)_2 \rightarrow CaSO_4 + Mg(OH)_2 \quad (1)$$

Another damage of concrete exposed to seawater is salt weathering, in which the accumulated salt crystals in concrete would expand due to water exposure and eventually cause internal stresses [11].

The knowledge of concrete fatigue influenced by seawater is limited since the simulation of real condition is rather hard to achieve. Arthur et al. [31] reported that seawater under certain conditions could extend the fatigue life of concrete beams. In their experiment, reinforced beams exposed partially (in the middle part) to seawater were subjected to unidirectional and reversal bending with the low frequency of 0.17 Hz (approximation of the frequency in the North Sea). During the first ten days, they found that accumulated deposits of calcium carbonate ($CaCO_3$) and magnesium hydroxide ($Mg(OH)_2$) in the cracks of the beams could slow down the deformation rate by the crack blocking effect and eventually increased the fatigue life. Since Arthur et al. [31] suggested that the applied stress range could be reduced by the effect of crack blocking upon unloading (when the beam is returning to its undeformed shape), it can be concluded that the beneficial effect of seawater (crack blocking behavior) depends on frequency. Paterson [32] performed similar experiment as Arthur et al. [31]. He reported the formation of deposits in cracks but with shorter fatigue life in seawater than in air. Even though Peterson found an increase in stiffness of the beams as the result of crack deposits, he suggested that the beneficial effect of seawater does not outweigh the degradation effect of seawater [32].

Chloride ion ingress is a major factor leading to the corrosion of reinforcement materials within reinforced concrete structures [33]. The presence of high alkalinity cement hydration products within the concrete forms a dense oxide film on the surface of the reinforcement, offering protection against corrosion [33]. However, chloride ions possess depassivation properties that can disrupt this protective film when they penetrate through connected pores and cracks in the concrete. This results in a decrease in pH within the surrounding pore solution, leading to the destruction of the protective film and subsequent corrosion of the reinforcement [34]. Apart from the penetration of chloride ions, the introduction of fatigue loading can accelerate the transmission of chloride ions by deteriorating the pore structure and creating microcracks within the concrete. Saito et al. [35] conducted an evaluation on the chloride ion permeability of concrete after both static and fatigue compressive loading. They observed that even when the static compressive loads reached 90% of the ultimate load, the chloride permeability of the concrete did not exhibit a significant increase. However, when subjected to fatigue loading with a maximum stress level of 60% of the ultimate load, the chloride permeability showed a clear increase. Furthermore, Ahn et al. [36] investigated the durability of reinforced concrete beams under the combined effects of loads and sea water corrosion. They applied a constant current to accelerate the corrosion of reinforcement materials and found that under fatigue loading, the corrosion of reinforcement materials occurred at a faster rate compared to static loading. Consequently, the ultimate bearing capacity of the beams was lower under fatigue loading conditions than under static loading.

Reinforced concrete corrosion is a complex issue that can be caused by a variety of factors, including carbonation, chloride attack, and salt weathering. The impact of seawater on fatigue capacity of reinforced concrete is an area that requires further investigation due to the limited knowledge and difficulty in simulating real-world conditions. While some studies have suggested that seawater can have a beneficial effect on concrete fatigue by reducing stress ranges through crack blocking, others have found that the degradation effect of seawater outweighs any potential benefits. Therefore, it is essential to continue researching the effects of seawater on concrete fatigue to better understand the mechanisms involved and develop more effective prevention and mitigation strategies.

2.4 Reinforcement

Most concrete structures contain some sort of reinforcement, and therefore, the effect of reinforcement on the fatigue life of concrete is of great importance. However, the fatigue of the steel bars is not the sole focus of interest in this review. Although it was reported that the final failure of reinforced concrete occurred in the steel [37, 38], the failure was preceded by extensive cracking in the concrete. The main desire for this kind of failure is to design under-reinforced components with ductile behavior to highly utilize the steel.

Aas-Jacobsen [1] performed fatigue tests of over-reinforced beams and columns. In this context, over-reinforced concrete is defined as a concrete element in which steel reinforcement reaches yield strain at loads higher than the load at which the concrete reaches failure strain. Although the specimens were designed to fail due to compression load, some of the specimens failed as a result of fatigue from reinforcement. He explained that the gradual increase in the plastic strain of concrete would increase the stress level of the steel. Subsequently, the redistribution of stresses from the concrete to the steel during cyclic loading would cause a decrease in the stress level of concrete [1]. This stress redistribution could potentially extend the fatigue life of reinforced concrete, assuming that the steel has sufficient capacity to withstand the stress increase. This phenomenon provides beneficial effects up to the point of yielding of compression reinforcement, where the concrete elements start to fail. It is preferable that the reinforcement yields first, allowing the structure to have large ductile strains upon failure. This will be a challenge when designing fatigue of concrete and reinforcement.

Stress redistribution might also cause a failure in the bond between reinforcement and concrete. Balazs [39] investigated the fatigue of bond by testing embedded reinforcement in concrete and measuring the slip during cyclic loading. He reported that the bond-slippage deformation was similar to the fatigue deformation of concrete with three-stage strain development, and cyclic degradation of the bond was caused by the progressive micro-crushing/micro-cracking in front of the protruding transverse ribs on the reinforcement. Interestingly, Balazs found that cyclic reversed loading would result in about four times higher slip compared to cyclic loading without a change in sign. According to Balazs, the bond strength is influenced by concrete strength, concrete cover, bar diameter, and confining effect [39]. However, Rehm and Elighausen [40] found no effect of concrete strength nor bar diameter when the fatigue bond strength is expressed as the ratio of static bond strength. Instead, in a more recent study, Sun et al. [41] found that bond strength is more influenced by the following factors: stirrups or any type of confinement, bond length, and loading parameters. According to the expression for bond stress between steel reinforcement and concrete (τ_{bond}) shown in Equation 2 [42], the amount of anchor length (L_{bd}) to withstand a steel force (F_{steel}) equal to yielding force is still less than 30 cm; d_{steel} is the diameter of steel reinforcement. Therefore, *Eurocode* [42] does not take the bond failure into account since it is assumed that the normal rules for reinforcement are in compliance. However, bond failure is more concerned with special structures. The case of Saito et al. [43] is an example of this, where the connection of the wind turbine tower and foundation failed prematurely due to bond fatigue.

$$\tau_{bond} = \frac{F_{steel}}{\pi * d_{steel} * L_{bd}} \quad (2)$$

Based on the discussion in this section, some limitations can be identified. First, the effect of fatigue on the reinforcement itself is not explored in this section, which could be an important aspect to consider in future research. Second, there is still limited understanding of the bond behavior between reinforcement and concrete under cyclic loading, especially in practical structures. Lastly, the available research is limited to laboratory testing, and further studies are needed to investigate the behavior of reinforced concrete structures in real-world conditions.

2.5 Fiber reinforced concrete

The use of fiber reinforced concrete (FRC) in engineering applications has caught the attention for the study of its behavior under cyclic loading. Paving applications, such as airports, bridge decks and industrial floor are common applications for FRC, which endure high cyclic loading during their service life [44]. Fiber volume content, fiber type and geometry are the main influential factors that differ the fatigue capacity of FRC.

The addition of fiber reinforcement has been reported to have a dual effect on the fatigue behavior of concrete. Fibers are able to bridge micro-cracks and retard their growth [45]. On the contrary, their presence increases the porosity and initial micro-crack density, resulting in strength reduction. The fiber volume significantly influences the overall outcome of these two competing effects [46]. Lee and Barr [45] collected various investigations that had carried out compressive fatigue tests [46-49] and flexural fatigue tests [48, 50-57] on plain and fiber reinforced concrete. Figures 4 and 5 show the linear regression lines for the results extracted from the works carried out using steel fibers with concentration (by volume) of 0.5% and 1.0% under compression and flexural loading, respectively. As seen in Figure 4, there is a slight degradation in the fatigue life of FRC relative to plain concrete subjected to compression loading. The reason behind it was attributed to the introduction of additional flaws within the concrete matrix by fiber addition that outweighed its benefits [48]. Contrary to the observations for compressive cyclic loading, there seems to be a significant benefit from the addition of fibers according to Figure 5. This means that FRC is more effective under flexural fatigue loading since fibers are able to bridge cracks and prolong fatigue life. Several other studies have found that steel fiber-reinforced concrete prisms exhibit superior fatigue life and less progressive deformation compared to plain concrete prisms when subjected to flexural fatigue tests [58-61].

Although there does not seem to be a general consensus about the effect of fiber inclusion on the fatigue endurance of concrete, the majority of researchers have, to a limited extent, found that fiber inclusion can be beneficial. Nevertheless, the quantitative nature of this benefit is hard to determine and need further investigations.

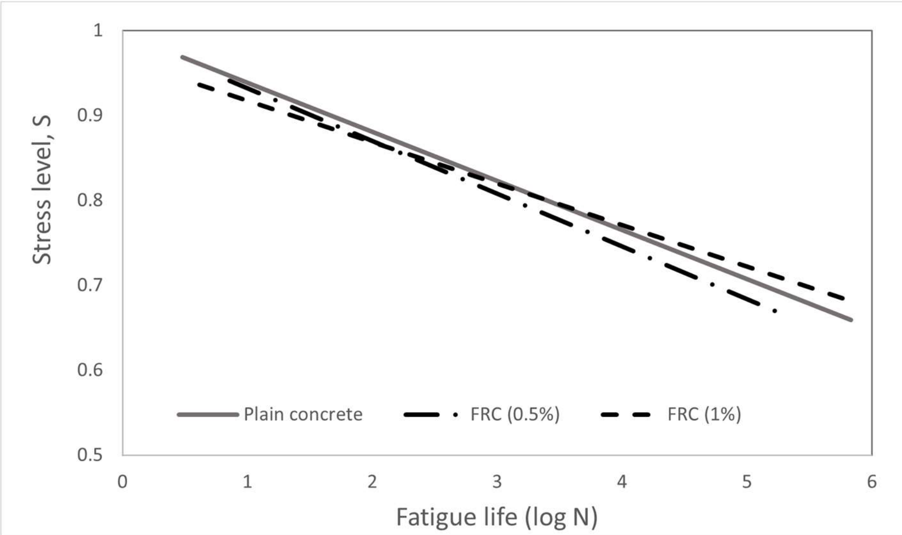

Figure 4 - Comparison between S-N curves for plain concrete and FRC under compression [45].

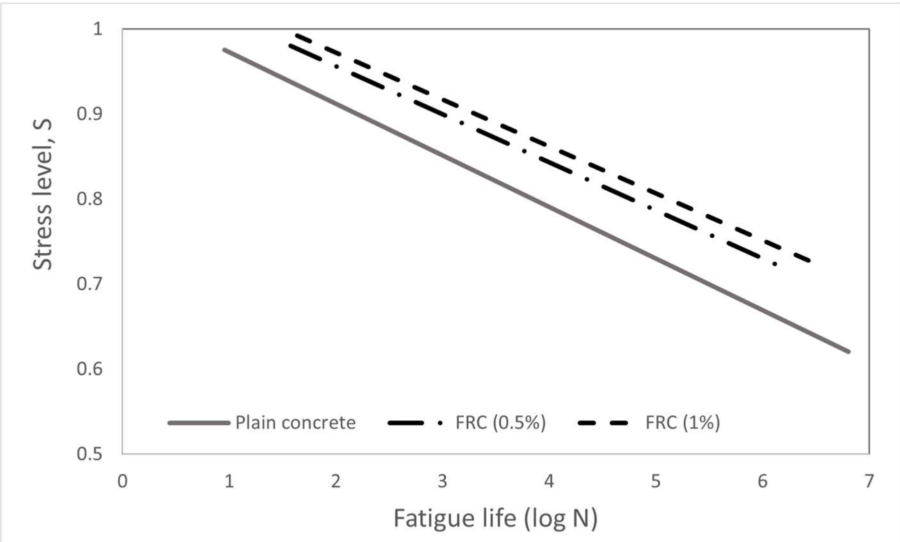

Figure 5 - Comparison between S-N curves for plain concrete and FRC under flexural loading [45].

2.6 Porosity

Concrete under cyclic loading sustains gradual fatigue damage. At the microscopic level, the damage resulting from the fatigue process and the birth and growth of micro-defects lead to progressive degeneration of internal structure. Microcracks initiate at the border of the pores and continue to progress through the path of minimal energy, which eventually leads to the connection of the pores [62]. As the pores are randomly distributed throughout the specimen, so is the damage. Thereby, understanding of how porosity would affect the service life of a concrete structure is crucial. Because of the complexity of this phenomenon, there is a lack of research in this area. Most of the relevant studies have focused more on the effect of cyclic loading on the quantity of pore structure [63-66]. They all agreed that the increase in pore volume is highly related to the expansion of cracks in the process of fatigue loading. Zhang [63] measured the porosity and pore size distribution of concrete at different bending fatigue stages using mercury intrusion method.

Considering the proposed regression relationship between cumulative pore volume P_{m0} and number of loading cycles N (Equation 3), it was reported that the concrete porosity increased by about 26% at failure point ($N/N_f = 1$).

$$P_{m0} = 0.0628 + 0.0163\, N/N_f \tag{3}$$

Vicente et al. [67] published a paper on the analysis of the relation between porous morphology and fatigue behavior of high-strength concrete. He performed an experiment with five series of concrete with different amounts of air entraining agent under compression-compression cyclic loading with a frequency of 2 Hz and S_{max} of 0.8. The correlation between the porosity and the fatigue life was found to be inverse, meaning that the greater the porosity, the lower the fatigue life. Moreover, the results revealed that the greater the percentage of small-size pores resulted in longer fatigue life.

2.7 Size effect

The effect of size on fatigue behavior can be associated with the moisture content, as discussed in Section 2.2. The water evaporation significantly influences the moisture state, meaning that a larger specimen tends to have a slower evaporation rate. The size effect also relates to monotonic strength, in which an increase in specimen size results in a strength reduction. This is shown in Figure 6 by Blanks and McNamara [68]. An intuitive explanation for this effect was provided by Neville [11]; as concrete consists of multiple components with variable strength, it is more likely that a specimen with a larger volume contains elements of low strength, though larger specimens reach a point where they do not experience any further reduction in strength. Most studies that investigated the size effect in fatigue concerned the theory of fracture mechanics and focused more on the development rate of cracks [69, 70]. Zhang et al. [69] simulated eight differently sized beams using their developed empirical equations for the crack mouth opening displacement to show the difference in fatigue capacity. Based on their simulations, they concluded that the larger specimens have shorter fatigue life. Their model is not valid for stress relative to the static modulus of rupture (MOR). If stress is normalized with respect to MOR, which is a size-dependent factor, the effect reverses, meaning that a larger beam would withstand a higher number of cycles compared to a smaller specimen.

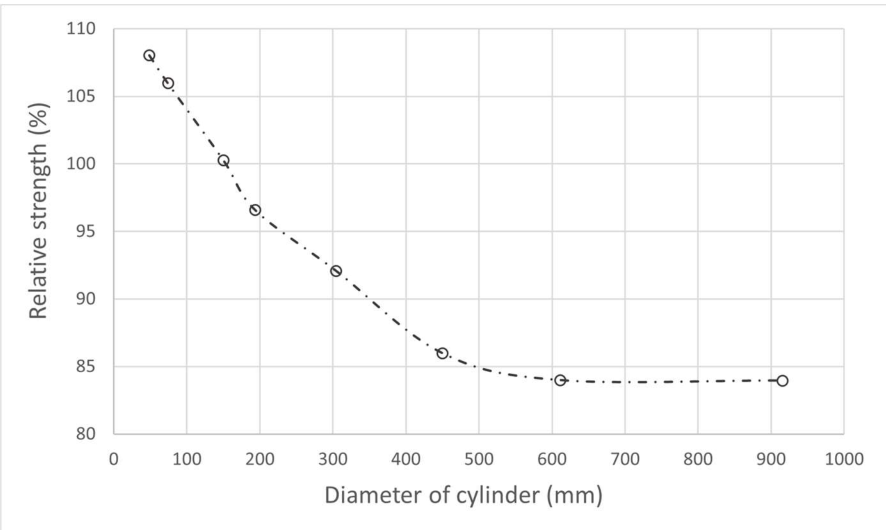

Figure 6 - Size-effect of cylinder on compressive strength [68].

2.8 Thermal response

The effect of temperature change on concrete properties is a well-known phenomenon. In one of the early studies by Assimacopoulos et al. [71] in 1959, the heat development due to cyclic loading was investigated. They monitored the surface temperature of cylindrical concrete specimens during cyclic testing with two different loading frequencies of 8.3 and 150 Hz. They concluded that the greatest change in temperature (around 52°C) occurred in the tests with the lowest minimum stress levels and highest loading frequency after one million load cycles. This could be expected since the lower minimum stress level corresponds to a higher stress range and a higher loading frequency corresponds to a higher rate of friction (lower rate of heat loss).

In a more recent investigation of temperature rise, Elsmeier and Lohaus [72] used infrared temperature sensors and thermal imaging to monitor temperature distribution. Their concrete specimens consisted of high-strength-concrete cylinders with a height of 180 mm and diameter of 60 mm under a wide range of maximum stress levels and loading frequencies between 1 and 10 Hz. In their experiment, high-stress level caused failure before the occurrence of heat accumulation. However, since the specimens with lower stress levels endured more cycles, they showed a larger total temperature rise. As for the temperature gradient, the maximum temperature was reported in the middle of the specimen and decreased towards the loading arrangement. They believed that the temperature gradient could cause additional stress within the specimens leading to a reduction in fatigue life. Likewise, they also reported that a higher loading frequency would cause a higher temperature rise. Otto et al. [73] found that cyclic tests with high frequency (10 Hz) cause premature failure. It was believed that the increase in drying of the specimens was the reason for premature failure. During fatigue testing, specimens' temperature reached 60°C. They conducted an experiment to evaluate the effect of the temperature increase on the monotonic compressive strength of the specimens. They reported that the temperature increase is related to the moisture state. For the sealed specimens, an increase in temperature reduces the compressive strength up to 20%. On the contrary, drying specimens gave 20 % increase in compressive strength. Thus, the influence of temperature highly depends on its ability to affect the moisture content of the specimen.

Hümme et al. [74] reported a distinct difference in ultimate strain due to the temperature changes. A large temperature development caused an increase in specimen length, leading to compressive strain reduction at failure. Though the maximum effect occurred at the failure point due to the temperature accumulation, some influences were observed during the entire strain development.

The effect of temperature is a variable in need of attention when assessing fatigue behavior. This is because of its interaction with various factors that might alter the outcome of the tests. Moreover, there is a lack of research on the effect of temperature on the fatigue life of concrete specimens submerged in water.

3 CONCLUDING REMARKS

In summary, the present review paper has identified and discussed eight significant factors that have a substantial impact on the fatigue performance of concrete. These factors can be classified into two main categories: material properties and environmental conditions. The factors include concrete composition, moisture content (both internal and external), exposure to seawater, reinforced concrete, fiber-reinforced concrete, porosity, size effect, and thermal response. These factors have been identified as having a significant impact on the fatigue capacity of concrete structures. The knowledge and understanding of these factors are critical for the design and maintenance of concrete structures to ensure their durability and longevity. Based on the reviewed literature, the following conclusions can be drawn:

- The impact of concrete composition on the fatigue performance of concrete structures has been examined, considering factors such as aggregate types, the addition of fly ash, and the water-to-cement ratio. The type of aggregate and the quantity of fly ash have been found to affect the bonding between minerals, particularly in the interfacial transition zone. Similarly, the water-to-cement ratio has been shown to influence fatigue strength in a manner comparable to the effect of exposure to external moisture on fatigue life.
- The impact of external moisture on concrete has been demonstrated to be significant, primarily due to the water-pumping effect within cracks as reported. It is recommended that standards carefully consider this effect to ensure comprehensive consideration.
- Some studies have indicated that seawater exposure can positively influence the fatigue performance of concrete structures by mitigating stress through crack blocking. However, other research has indicated that the detrimental effects of seawater, such as chloride ion ingress leading to reinforcement corrosion, outweigh any potential benefits.
- The impact of stress redistribution from concrete to reinforcement and bond slip has been examined, revealing a positive influence from reinforcement on the fatigue behavior of concrete structures. Furthermore, the influence of fiber reinforcement has been addressed. While there was no definitive consensus regarding the effect of incorporating fibers on the fatigue endurance of concrete, a majority of researchers have observed some level of benefit. However, determining the quantitative extent of this benefit remains challenging and requires further investigation.
- The review has also discussed the impact of porosity, size effect, and thermal response on the fatigue behavior of concrete structures.

The mentioned factors often interact with one another, making it difficult to isolate and consider the effect of each factor independently. As such, there is a need for further research on the fatigue behavior of concrete, with a focus on each phase of fatigue, and for investigations to be organized in a way that allows for the isolation of specific factors.

The absence of a standardized protocol for conducting fatigue tests poses a challenge in drawing conclusive comparisons and analyses of published results. Inconsistencies and contradictions in the literature further hinder the ability to make definitive statements about the effects of various test parameters on fatigue behavior. It is therefore imperative to deepen our understanding of the underlying mechanisms of fatigue to move beyond solely empirical formulas to analytical solutions. With such an improved knowledge base, design codes may be able to incorporate additional influential factors beyond stress level and loading amplitude, which currently dominate code requirements. As research in this field continues to evolve, so too will our understanding of fatigue mechanisms and the design codes that govern them, suggesting significant potential for future development and inquiry in the realm of concrete fatigue.

This paper (Part II) is the second one in a series of two papers devoted to the same subject. The first paper (Part I) can be found in the very same issue of NCR [75}.

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