Research Paper

Resonance fatigue testing on high-strength self-compacting concrete

Thomas, C.*[1]; Sainz-Aja J.[1]; Setien, J.[1]; Cimentada, A. [1]; Polanco, J.A.[1]

LADICIM (Laboratory of Materials Science and Engineering), University of Cantabria. E.T.S. de Ingenieros de Caminos, Canales y Puertos, Av./Los Castros 44, 39005 Santander, Spain

* Correspondence: thomasc@unican.es

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Featured Application: This research compares the fatigue characterization of a high-strength self-compacting concrete carried out at moderate frequency (10 Hz) and at very high frequency (100 Hz). This comparison shows that the increase up to this frequency range reduces fatigue life of concrete.

Abstract: Concrete structures are increasingly affected by fatigue damage, while new slender building structures with greater mechanical requirements make it necessary to deepen knowledge of their behaviour under fatigue loading. In this research, high-strength plain concrete was studied under two different frequencies of cyclic compressive stress. Wöhler curves were obtained in two different ways, on the one hand, applying a uniform frequency of 10 Hz and, on the other hand, applying the specimen resonance frequency. The results show two different types of behaviour. A reduction in fatigue life was observed in those concretes tested at very high frequency. When loads were applied at resonance frequency, they did not seem to modify the breaking mechanisms of the concrete subjected to fatigue.

Keywords: Fatigue; high-strength concrete; plain concrete; Wöhler; frequency; resonance; fatigue limit, fatigue life.

1. Introduction

Building structures, bridges and railway sleepers are components subjected to cyclic loading that can cause the loss of mechanical properties or even structural collapse under fatigue loading [1–6]. Historically, several researchers have studied the empirical fatigue behaviour of concrete. In 1852, A. Wöhler started analysing the phenomenon of fatigue in railway systems. Subsequently, H. Gerber and Goodman developed methodologies for calculating fatigue life according to the applied stress level. In 1886, J. Bauschinger confirmed the results obtained by Wöhler and defined the elastic limit of the materials. In 1903, J. A. Erwing observed the appearance of microcracks on the surfaces of the specimens tested under fatigue that would cause the subsequent appearance of cracks due to the load cycles leading to the failure. In 1910, O.H. Basquin proposed empirical laws that characterize the fatigue limit of materials. In 1924, A. Palmgren developed fatigue damage accumulation models, which served as the basis for the models that Miner subsequently developed in 1945.

In fatigue tests on concrete under compression, the load frequency is usually in the range 1-15 Hz [7–9]. It is well known that using frequencies lower than 1 Hz reduces the fatigue limit due to an increase in the creep damage [5,9,10]. The reason for using 15 Hz as the upper limit is not clear; there is little research analysing this matter. Modern technical development allows us to use equipment that can exceed 100 Hz, referred to as high-frequency fatigue [11] and even to perform tests at ultra-high frequency (frequency of approximately 20 kHz) [12]. As is expected, high-frequency testing supposes a significant reduction in the time to reach the limit of fatigue of a material. However, doubts arise regarding the validity of comparisons with low-frequency tests [13,14].

There are different testing procedures to characterize concrete under fatigue. The most usual technique is the Wöhler curve, also known as S-N curve [15–17]. Other methodologies have been used by different authors such as the staircase or Locati methods [13,14]. There are new technologies such as micro-CT that have been used to understand how fatigue affects concrete, which can determine the damage mechanisms in concrete subjected to fatigue loads [4,5,18–22].

Nowadays, the use of self-compacting concretes is a common option, both for economic and environmental reasons. From the economic point of view, it can lead to a reduction in execution costs [23] and more durable concrete [24,25]. From the environmental viewpoint, self-compacting concretes are one of the most eco-friendly types of concrete [26,27]. As Alyamac et al. state [26], self-compacting is one of the most eco-friendly types of concrete because waste materials have always been used in self-compacting as the mineral powder, such as marble powder or fly ash. In addition, it facilitates the design of high-performance concretes since it minimizes the water-cement ratio [3,28].

This paper analyses the effect of increasing the frequency of testing on specimens subjected to cyclic loads. A high-strength concrete was characterized under moderate frequency fatigue stresses (10 Hz). Next, high-frequency resonance fatigue tests (≈100 Hz) were carried out on the same material and the results obtained were compared. If similar results are obtained, a new methodology could be defined for the characterisation of fatigue concrete which, due to its shorter duration, is more economical. In case of obtaining different results, this would imply that when designing a structure that can be subjected to this type of load (for example: support structures of industrial machines, big engines and/or turbines) the effect of high frequency must be taken into account.

In the case of concrete, the first variable to consider is the compression load or loads that will be applied to the specimen during the test. In order to carry out a study about the fatigue behaviour of a certain material, the type of fatigue to be analysed must first be defined. The fatigue that is applied to these concretes is exerted by a dynamic machine that, in this case, can work in position control or in load control regimes. In the first case, the fatigue interval will be determined by two positions, the lower limit and upper limit of the interval. However, in concrete, this type of test must be discarded, since the difficulty lies in the well-known fact that it is a particularly rigid material and not very deformable, so position control would introduce a very large uncertainty in the stress-strain relationship. For this reason, it is recommended to carry out all fatigue tests on concrete in load control regime. In this sense, the characterization is undertaken between two stresses, σ_i and σ_j, as the lower limit and upper limit of the voltage range for which the material is subjected to fatigue.

One of the questions that arises before the study is whether high-frequency fatigue could have a negative effect on the life of concrete by accumulation of heat energy, as happens with polymeric materials, given that there is greater heating in the case of fatigue at high frequency than at low frequency.

2. Materials and methods

2.1. Materials

A commercial self-compacting concrete was used with 400 kg/m^3 of Portland cement type 52.5 and rounded aggregate of maximum size 12 mm, due to it is a commertial product under patent it was not possible to detail the mix proportions. With these mix proportions, 6 series were made on different days. The different batches enable the verification of the quality and homogeneity of the materials and the methods used. From each of these 6 series, characterization tests were carried out in a fresh state, compressive strength tests were carried out with samples at 7 and 28 days, and 20 cylindrical specimens of 200 mm high and 100 mm in diameter were manufactured for fatigue characterization. All the specimens used to determine the compressive strength and elastic modulus tests were polished on the top side to ensure proper axiality of the loads.

2.2. Concrete workability

In the quality control process of each mix, a slump flow test was performed according to standard EN 12350-5 [29]. This standard takes as a reference the test described in standard EN 12350-2 [30]. During these tests the t_{500} and D value were registered.

2.3. Mechanical properties

Moderate frequency fatigue requires a high number of long duration tests, in total it took nearly one year to obtain the Wöhler curve. The order of testing the specimens was by mix, that is, first all the specimens of the first mix were tested, then all the specimens of the second series were tested and so on. In order to ensure that the concrete would have stable behaviour, test specimens were not used until 90 days old. Anyway, before starting with the first specimen of each mix, three specimens were selected of this mix, which were used to determine the compressive strength and elastic modulus for the first fatigue test. The compressive strength was determined according to EN 12390-3 and EN 13290-3/AC [31] and Young's modulus according to EN 12390-13 [32]. In addition, to determine the elastic modulus, two strain gauges were installed in the longitudinal direction on two diametrically opposed specimen generators.

2.4. Fatigue testing under moderate frequency

To determine and analyse the evolution of the mechanical properties of the specimens during the fatigue tests, two strain gauges were installed in the longitudinal direction on two diametrically opposed cylinder generators. These tests were performed on a servo-hydraulic machine with a maximum capacity of 1000 kN.

2.4.1. Wöhler curve

The tests performed to obtain the Wöhler curve involved fatigue tests with a fixed minimum value of 12 MPa and a maximum stress value between 71.5 and 47.3 MPa depending on the test. The end of these tests is either when the specimens break or when they endure 10^7 cycles without breaking. The Wöhler curve or S-N curve can be constructed with the number of cycles to breakage and the stress range of the test (σ_{max} -σ_{min}).

Since the evolution of the specimen strain was digitally recorded, it was possible to identify the effect of fatigue on the specimen strain, elasticity modulus of the specimen and remaining strain.

2.4.2. Morphological analysis of fractures

Once the specimens break, a visual analysis of the fracture surfaces was performed to identify the mechanisms that led to breakage.

2.5. Fatigue testing at high frequency

In order to reduce the testing time, the test frequency was increased. To do so, a resonant fatigue machine was used, which performs the fatigue tests at the resonance frequency of the test machine assembly. This option enables tests to be performed at a frequency of approximately 100 Hz, that is, the duration of the tests was reduced to a tenth. As in the case of moderate frequency tests, all specimens were polished on the top side to ensure proper axiality of the loads

2.4.1. Wöhler curve

The tests carried out to create the Wöhler curve consisted of fatigue tests with the same minimum stress value (12 MPa) and a maximum stress value between 60 and 35 MPa depending on the test. The end of these tests is either when the specimens break or when they endure $2{\cdot}10^7$ cycles without breakage. In this case, as the duration of the tests is much shorter, the run out of the tests was defined as twice as many cycles. With the number of cycles to breakage and the stress range of the test, as in the case of tests at moderate frequency, it is possible to plot the Wöhler curve.

As these tests are performed at a high number of cycles per second (approx. 100), the equipment available to register the strain gauge value for the moderate-frequency tests is not capable of recording data at the necessary sampling frequency for the strain data to be representative, so in these cases the evolution of the specimen strain was not recorded.

2.4.2. Morphological analysis of fractures

Once the test specimens had been broken, the breakage surfaces of the test specimens were analysed. As in the case of moderate-frequency tests, these breakage surfaces enable the determination of the damage mechanisms present in the concrete specimens.

3. Results and discussion

3.2. Workability tests

Table 2 shows the workability test results of each of the 6 series.

Table 1. Workability test results.

Mix	Slump flow [mm]	t_{500} [seg]
Series 1	785	4
Series 2	810	5
Series 3	710	4
Series 4	710	4
Series 5	740	4
Series 6	725	4

3.1. Mechanical properties

Figure 1 shows the compressive strength of the mis proportion as function of time. This curve was obtained by mean of six different series, each of them used to determine the results at 7, 28 and the beginning of the fatigue tests of the samples manufactured from this series. The average Young's modulus of the same six mixes is 42.45 GPa.

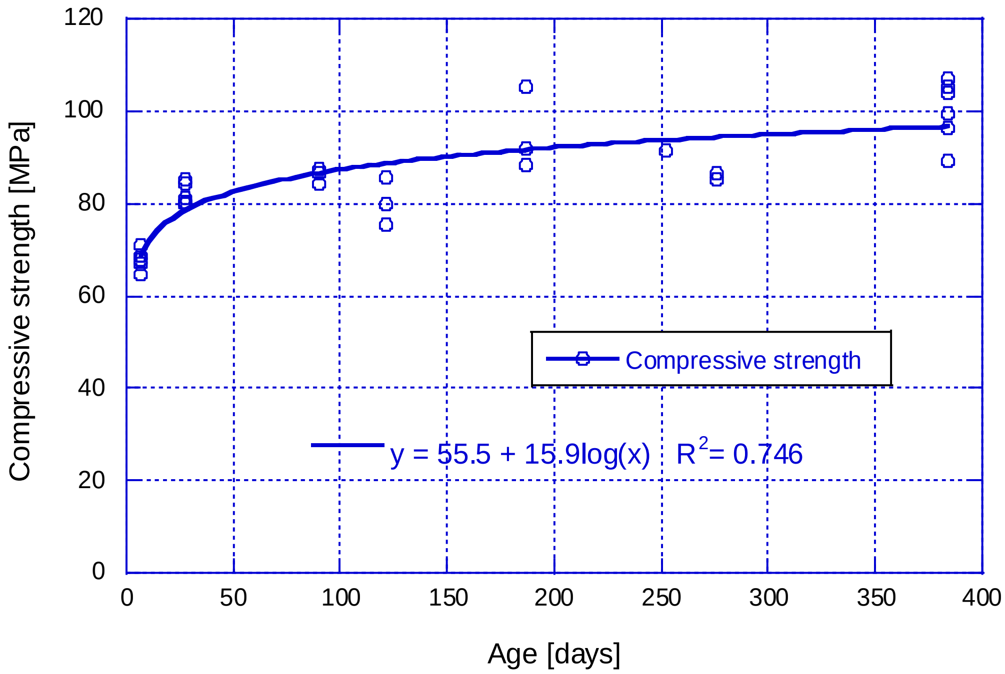

Figure 1. Compressive strength.

3.3. Moderate-frequency fatigue tests

3.3.1. Wöhler curve

Figure 2 shows the Wöhler curve obtained at moderate frequency. In this figure, the results are classified depending on the series and refer to the static compressive strength of each one. The data shown in Figure 2 had been normalized respect to compressive strength, in this way it is possible to predict the fatigue life of a concrete without depending on the concrete age.

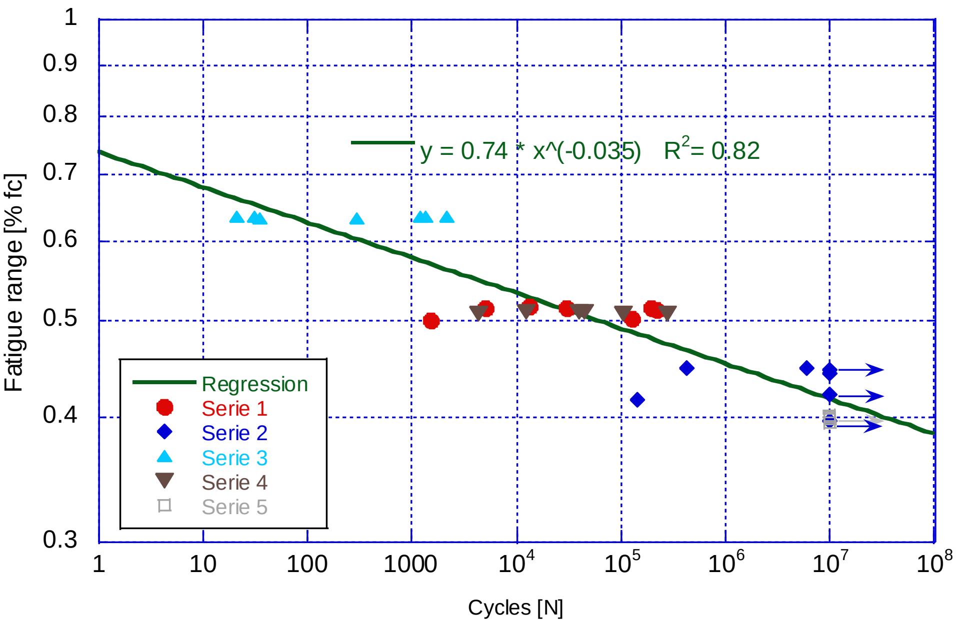

Figure 2. Concrete Wöhler curve at moderate frequency.

Series 1:

For dynamic tests, the samples were subjected to an amplitude of 44 MPa. The values obtained, although very variable, are within the high cycle fatigue but before the concrete endurance. This dispersion is because this type of damage is magnified by the irregularities present in concrete, such as the pores.

Series 2:

Regarding the dynamic tests, the samples were subjected to amplitudes ranging from 35.3 to 40.8 MPa. The dispersion of the fatigue results reflects the dispersion of the static tests, which can be assumed to be due to the manufacturing process, polishing and/or slight modifications of the mix proportions.

Series 3:

The amplitude ranges of the dynamic tests of this series are the largest of all the tests; 59.5 MPa and it is assumed that the results for these stress levels are around one hundred to one thousand cycles, however, the results of low numbers of cycles are related to specimens local defects, which marks the behavior of the component being extremely difficult to predict its fatigue life and, consequently, a great scatter could be find.

Series 4:

Dynamic tests were performed with an amplitude of 48 MPa. The records of the dynamic tests are those expected due to their similarity to the stress ranges of Series 1.

Series 5:

The dynamic tests were carried out with the lowest amplitude of all the tests; 38 MPa, which is in agreement with the results obtained, all the specimens withstood the 10^7 cycles. Due to all tests were performed with the same stress values and all the tests were stopped at 10^7 cycles it seems just one point in Figure 2 when there are actually seven.

From the tests carried out, it can be concluded that the endurance of the concretes tested is around 50% of the material's compressive strength ($0.5*\sigma_{max}$). Figure 3 to Figure 5 show an example of the behaviour of the specimens in the tests that successfully pass the 10^7-cycle run out in the test at moderate frequency. Figure 3 shows the evolution of the specimen strain as a function of the number of cycles. Figure 4 shows the remaining strain on the specimen as a function of the number of cycles. Finally, Figure 5 shows the evolution of the elastic modulus as a function of the number of cycles.

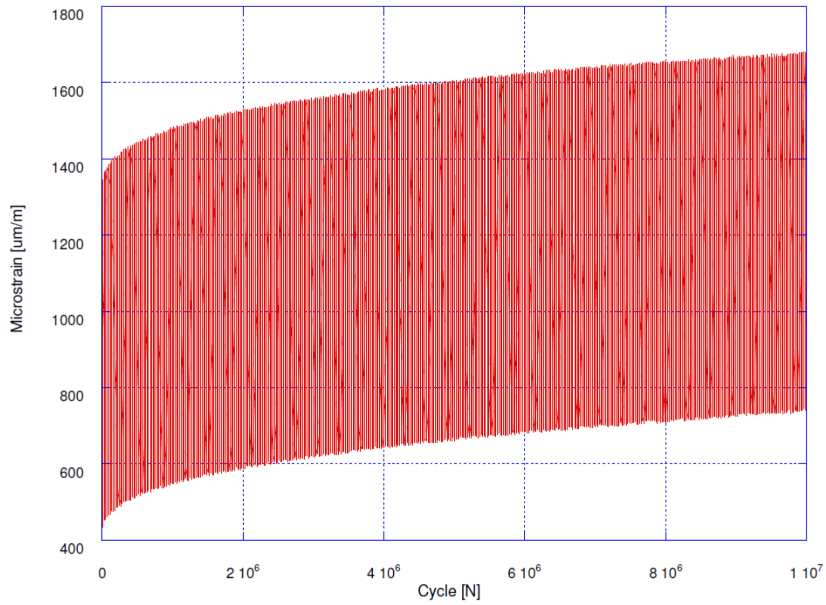

Figure 3. Strain Vs. cycles in a passing moderate-frequency fatigue test.

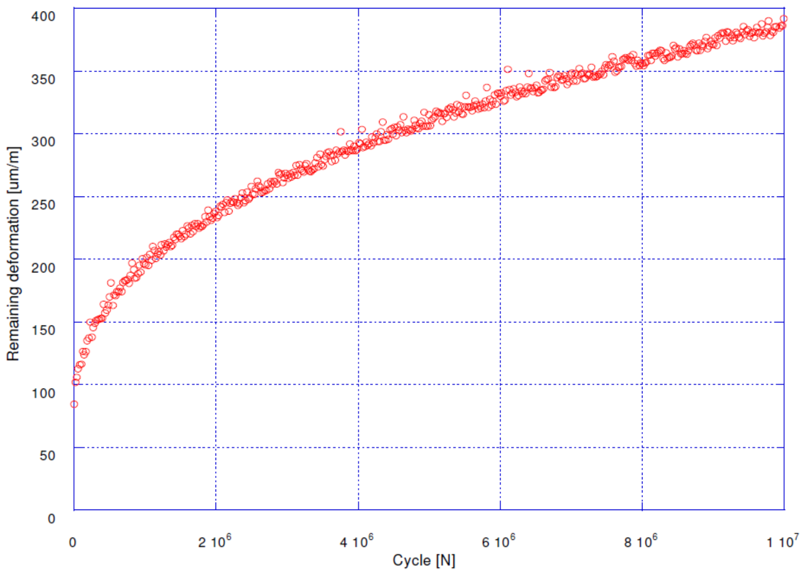

Figure 4. Remaining strain vs. cycles in a passing moderate-frequency fatigue test.

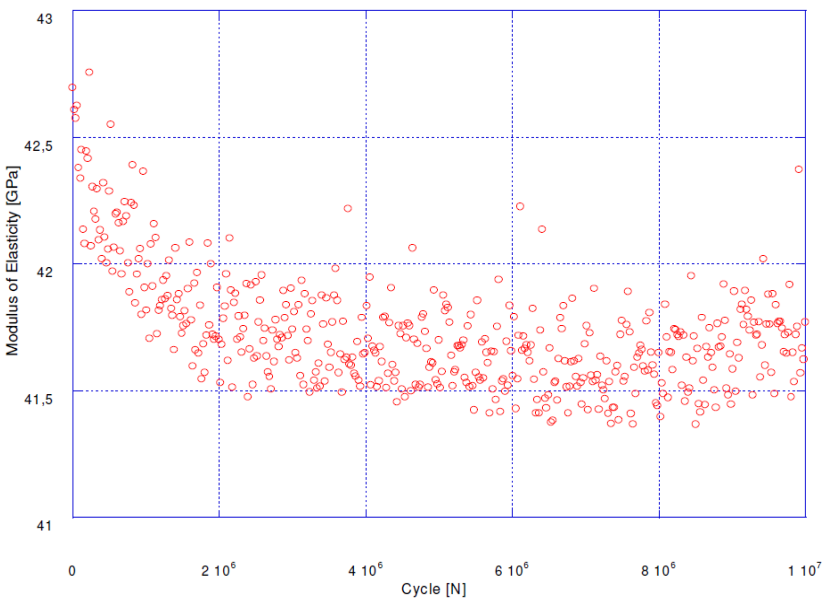

Figure 5. Modulus of elasticity VS. cycles in a passing moderate-frequency fatigue test.

From Figure 3 it can be seen that the concrete strain always increases. This fact is consistent with the results of other authors that state that the concrete has no fatigue limit, since the damage suffered by the concrete is a consequence of the growth of microcracks inherent to concrete [13,14]. When the specimens resist the test without breaking, the remaining strain values always increase, see Figure 4. This parameter is an indicator of the increase of damage that the specimen is suffering, although, due to the limit of cycles associated with endurance, in this case 10^7 cycles, and the reduced velocity of the increase of damage, the specimens do not break. In the case of strain range, it remains approximately constant. If these amplitude values are kept constant, the elastic modulus will stabilize under dynamic conditions, see Figure 5.

Figure 6 to 8 show that it is possible to see examples of the same type of curves already mentioned, but in this case, of a specimen which is not able to resist the number of cycles corresponding to the endurance and, consequently, the effect on each one of these parameters can be seen if it is close to breakage.

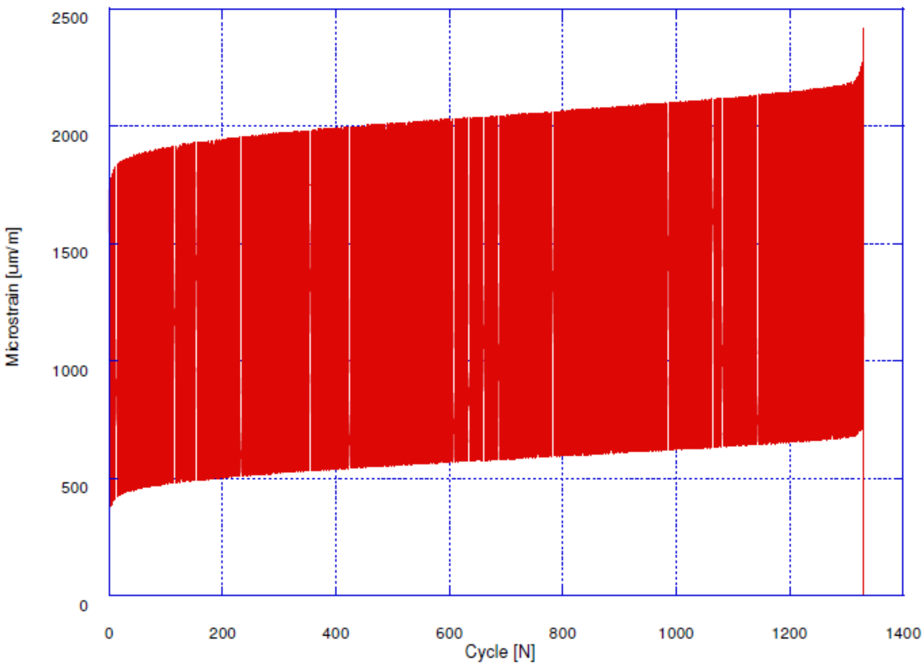

Figure 6. *Strain vs. cycles in a non-passing moderate-frequency fatigue test.*

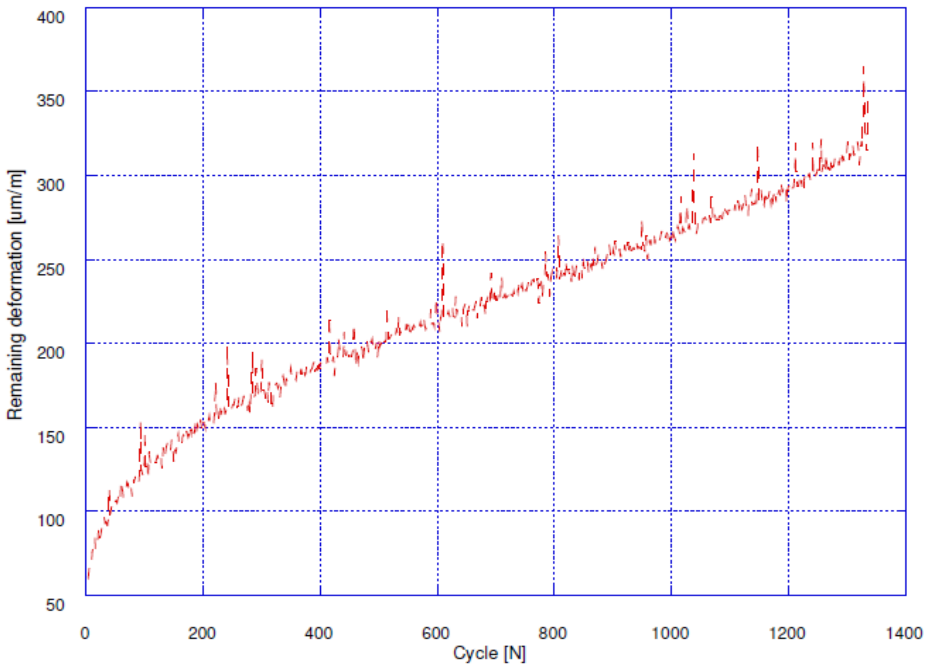

Figure 7. Remaining strain vs. cycles in a non-passing moderate-frequency fatigue test.

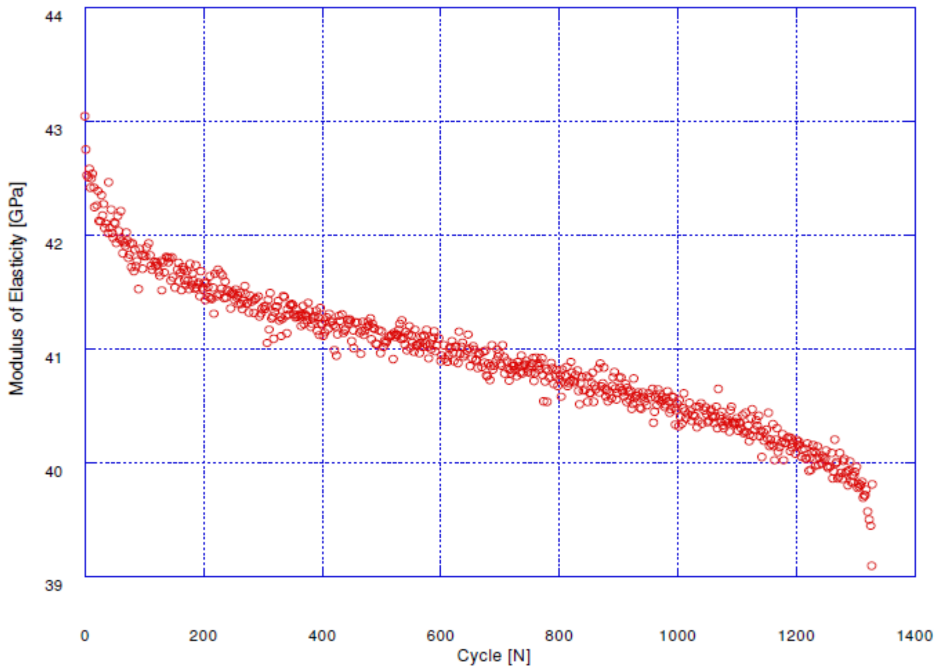

Figure 8. Modulus of elasticity vs. cycles in a non-passing moderate-frequency fatigue test.

Figure 6 shows that, as in the case of specimens that pass the run out, strain always increases with the number of cycles. In this type of tests, you can see the 3 phases observed by other [13,14] authors. A first one in which the speed of evolution of the strains is becoming slower, known as phase A. A second in which the growth rate of strain is approximately constant, known as phase B. This is the phase of greatest importance since it is normally the phase that monopolizes the greatest number of cycles. Finally, there is a third phase in which the speed of the strain increases, leading to a rapid breakage of the specimen. In the case of the remaining strain, it can also be seen that it always continues to increase and that it presents the same three phases previously commented. In the case of the evolution of the elastic modulus, it can be seen that there are the same 3 phases, but in an inverse sense, that is, it always decreases.

When comparing these 6 graphs, it can be suggested that there are three different types of damage suffered by the concrete that are responsible for the 3 phases of behaviour. The evolution of these parameters in phase A is mainly a consequence of these loads having been applied for the first time, giving rise to the formation of cracks. This type of damage has less and less effect, since these cracks become stabilized after a few cycles. The second type of damage is present throughout the life of the concrete and is represented by an increase in the remaining strain, which is related to creep damage and is dominant in phase B. Then, there is a third type of damage that mainly affects the evolution of the elastic modulus and is related to fatigue damage. This is the dominant damage mechanism in phase C. These last two damage mechanisms will gradually reduce the mechanical properties of the concrete until it is no longer able to withstand the loads to which it is subjected. Although both types of damage are subcritical, the first type of damage acts throughout the test, while the second is a damage mechanism that requires minimum internal damage values to start damaging the concrete. These hypotheses fit with the existing theory of fracture mechanics usually applied to metals.

3.3.2. Morphological analysis of fractures

Once the tests were completed, in those specimens that had successfully passed the tests, the breakage surfaces were analysed to identify the damage mechanisms that occur in the concrete. Two main types of breakage were distinguished, see Figure 9 and 10.

Figure 9. Fracture surface of a sample broken during a fatigue test, mode 1.

The resulting cone shown in Figure 9 is undoubtedly a perfectly distributed fatigue break. This morphology shows that, during the execution of the test, the distribution of the loads was homogeneous.

Figure 9 shows the presence of large pores, distributed in a disperse way inside the concrete. The pores are areas of concentration and crack propagation. The premature rupture of this specimen may be due to the defects mentioned above.

Figure 10. Fracture surface of a sample broken during a fatigue test, mode 2.

Figure 10 (left) the formation of breakage planes perpendicular to the base can be seen, which is an indication of a higher stress concentration in the corresponding fibres. The heterogeneous distribution of stresses, presumably due to the different flatness of the load application surfaces, could cause the premature breakage of a fragment of the specimen reducing its resistant capacity. With regard to the process of formation and growth of the cracks that lead to the breakage of the specimens, based on the results of Karr et al. [12] and Sainz-Aja et al. [20], both performed tests to determine the cracking process of the fatigued concrete by mean of computerized tomography at ultra-high and moderate frequency respectively, it can be assumed that this initiation appears in the interphase paste-aggregate.

3.4. High-frequency fatigue tests

3.4.1. Wöhler curve

Figure 11 shows a comparison of the Wöhler curves obtained at moderate frequency (MF) and at high frequency (HF).

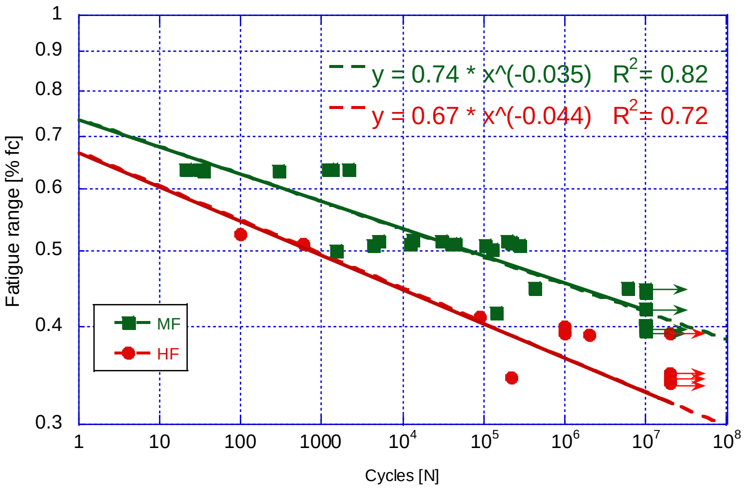

Figure 11. Comparison of the concrete Wöhler curve obtained at moderate and high frequency.

When comparing these two curves, firstly, we can see that performing fatigue tests at resonant frequency reduces the fatigue life of the specimens. It can also be seen that the influence of carrying out the tests at moderate frequency or at very high frequency becomes greater as the number of cycles carried out increases. These results agree with the results provided by Sainz-Aja et al. [33], who found that tests carried out at very high frequency can increase the temperature of the concrete, which can increase the creep damage and, therefore, accelerate the second type of damage, so reducing the fatigue life of the material. As this type of damage accumulates throughout the whole test, it is logical that the difference between the tests at high and low frequency becomes much greater as the number of cycles increases, or in other words, the greater the duration of the test.

From the results of this research and information obtained from the literature mentioned in the introduction, it is observed that the fatigue limit depends on test frequency. Figure 12 is a croquis which pretends to graphically represent the effect of frequency on concrete behaviour, it shows the evolution of the fatigue limit as a function of the frequency. It can be seen that, if the frequency is low (<1 Hz) blue box, the fatigue limit of the concrete reduces due to the increment of creep damage as a consequence of the greater duration of tests and consequently the increase of creep damage [5,9,10]. In the range of moderate frequency (1-15 Hz) (green box) the fatigue limit remains approximately constant [7–9]. In the case of testing at very high frequencies (red box), the specimens increase in temperature, which implies greater creep damage and, consequently, a reduction in the fatigue limit [11,33]. In the next frequency range (yellow box) there were not found results by other authors working in this range, so a linear evolution is supposed.

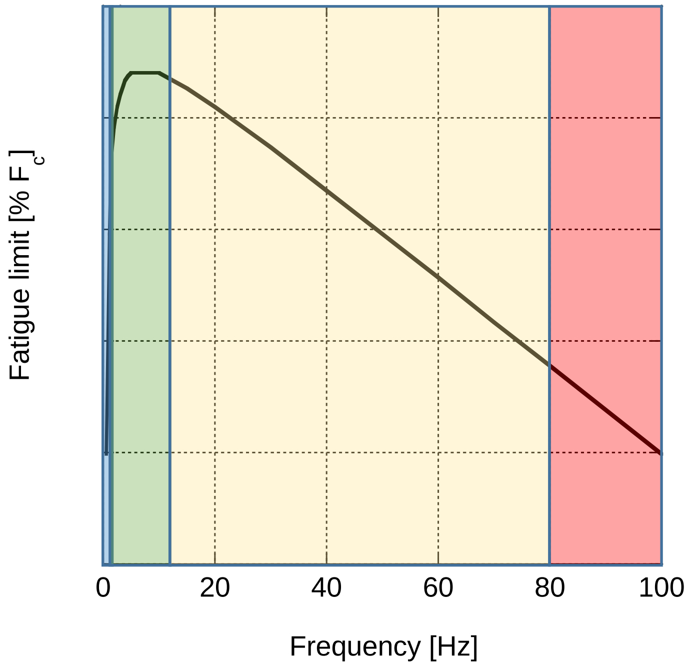

Figure 12. Evolution of the fatigue limit as a function of the frequency.

As can be seen, the range defined as the appropriate range for fatigue characterization (1-15 Hz) provides the highest fatigue limit results. This can lead to an inconsistency between test conditions and operating conditions resulting in the collapse of the structure.

Once the great effect that creep has in fatigue tests has been proven in this work, as a future research line it would seem logical to develop a tool similar to as FAD (Failure Assessment Damage). FAD is usually used in structural integrity studies [34,35]. Based on fracture toughness and plastic collapse stress ratios this FAD could define if it is possible to guarantee that it is in a safe situation or if not [36]. Due to the effect of load conditions such as fatigue or creep the damage value changes, and consequently, the point in the FAD which analysis the integrity of the element. Modifying the variables used in a FAD, and defining new damage parameters based on fatigue (varying as function of cycles and loading conditions) and creep (varying as function of time and working conditions) a new modified FAD model could be developed which could help to estimate the remaining working life of the structure.

3.4.2. Morphological analysis
of fractures

In Figure 13, an example can be seen of the fracture surfaces of concrete specimens after failing different fatigue tests, on the right, one obtained from fatigue tests at moderate frequency and on the left, one tested at high frequency.

Figure 13. Comparison of the concrete fracture surface obtained at moderate (right) and high frequency (left).

It was found that the breaking surfaces at moderate and very high frequencies were similar. This is because the dominant type of damage in phase C, which is the phase that defines the breakage mechanisms, is independent of the test frequency.

4. Conclusions

The evolution of concrete structures and more optimized design have led to a situation in which concrete structures can be damaged due to repeated stresses below their mechanical strength limit, i.e. they are susceptible to fatigue damage. In this paper, high strength self-compacting concrete was characterized at both moderate and very high frequencies, obtaining the following conclusions:

- It was confirmed that for moderate frequency tests, the 3 stages of evolution identified by other authors are observed.
- Testing at very high frequency has been shown to reduce fatigue life as a consequence of increasing the temperature and consequently increasing the damage due to creep, i.e. type 2 damage.
- For the correct interpretation of fatigue results, it would be necessary to use a tool such as FAD (Failure Assessment Damage), which enables both fatigue damage and creep damage to be taken into account.
- The range defined as appropriate for fatigue characterization (1-15 Hz) provides the highest fatigue limit results. This can lead to an inconsistency between test conditions and operating conditions, resulting in the collapse of the structure.

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References

[1] Alliche A. Damage model for fatigue loading of concrete. Int J Fatigue 2004;26:915–21. https://doi.org/10.1016/J.IJFATIGUE.2004.02.006.

[2] Ferreño D, Casado JAJAJA, Carrascal IAIAIAIA, Diego S, Ruiz E, Saiz M, et al. Experimental and finite element fatigue assessment of the spring clip of the SKL-1 railway fastening system. Eng Struct 2019;188:553–63. https://doi.org/10.1016/j.engstruct.2019.03.053.

[3] Sainz-Aja J, Carrascal I, Polanco JA, Thomas C, Sosa I, Casado J, et al. Self-compacting recycled aggregate concrete using out-of-service railway superstructure wastes. J Clean Prod 2019;230. https://doi.org/10.1016/j.jclepro.2019.04.386.

[4] Xiao J, Li H, Yang Z. Fatigue behavior of recycled aggregate concrete under compression and bending cyclic loadings. Constr Build Mater 2013;38:681–8. https://doi.org/10.1016/j.conbuildmat.2012.09.024.

[5] Skarżyński Ł, Marzec I, Tejchman J. Fracture evolution in concrete compressive fatigue experiments based on X-ray micro-CT images. Int J Fatigue 2019;122:256–72. https://doi.org/10.1016/j.ijfatigue.2019.02.002.

[6] Sainz-Aja JA, Carrascal IA, Ferreño D, Pombo J, Casado JA, Diego S. Influence of the operational conditions on static and dynamic stiffness of rail pads. Mech Mater 2020;148.

[7] Medeiros A, Zhang X, Ruiz G, Yu RC, Velasco M de SL. Effect of the loading frequency on the compressive fatigue behavior of plain and fiber reinforced concrete. Int J Fatigue 2015;70:342–50. https://doi.org/10.1016/j.ijfatigue.2014.08.005.

[8] Murdock JW. A critical review of research on fatigue of plain concrete. University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station.; 1965.

[9] Rep C. CONSIDERATIONS FOR DESIGN OF CONCRETE STRUCTURES SUBJECTED TO FATIGUE LOADING. J Am Concr Inst 1974;71:97–121.

[10] European Concrete Committee. Ceb Committee GTG 15. Fatigue of concrete structures. CEB Bulletin d'information, 1988;Nº 188.

[11] Sainz-Aja J, Thomas C, Polanco JA, Carrascal I. High-Frequency Fatigue Testing of Recycled Aggregate Concrete. Appl Sci 2019;10:10. https://doi.org/10.3390/app10010010.

[12] Karr U, Schuller R, Fitzka M, Denk A, Strauss A, Mayer H. Very high cycle fatigue testing of concrete using ultrasonic cycling. Mater Test 2017;59:438–44. https://doi.org/10.3139/120.111021.

[13] Thomas C, Setién J, Polanco JAA, Lombillo I, Cimentada A. Fatigue limit of recycled aggregate concrete. Constr Build Mater 2014;52:146–54. https://doi.org/10.1016/J.CONBUILDMAT.2013.11.032.

[14] Thomas C, Sosa I, Setién J, Polanco JA, Cimentada AI. Evaluation of the fatigue behavior of recycled aggregate concrete. J Clean Prod 2014;65:397–405. https://doi.org/10.1016/J.JCLEPRO.2013.09.036.

[15] Hwan Oh B. Fatigue analysis of plain concrete in flexure. J Struct Eng (United States) 1986;112:273–88. https://doi.org/10.1061/(ASCE)0733-9445(1986)112:2(273).

[16] Bizindavyi L, Neale KW, Erki MA. Experimental investigation of bonded fiber reinforced polymer-concrete joints under cyclic loading. J Compos Constr 2003;7:127–34. https://doi.org/10.1061/(ASCE)1090-0268(2003)7:2(127).

[17] Lee MKK, Barr BIGIG. An overview of the fatigue behaviour of plain and fibre reinforced concrete. Cem Concr Compos 2004;26:299–305. https://doi.org/10.1016/S0958-9465(02)00139-7.

[18] Thomas C, de Brito J, Gil V, Sainz-Aja JA, Cimentada A. Multiple recycled aggregate properties analysed by X-ray microtomography. Constr Build Mater 2018;166:171–80. https://doi.org/10.1016/J.CONBUILDMAT.2018.01.130.

[19] Thomas C, de Brito J, Cimentada AIAI, Sainz-Aja JAJ. Macro- and micro- properties of multi-recycled aggregate concrete. J Clean Prod 2019;In press:118843. https://doi.org/10.1016/j.jclepro.2019.118843.

[20] Sainz-Aja J, Carrascal I, Polanco JA, Thomas C. Fatigue failure micromechanisms in ed aggregate mortar by μCT analysis. J Build Eng 2019:101027. https://doi.org/10.1016/J.JOBE.2019.101027.

[21] Li Q, Huang B, Xu S, Zhou B, Yu RC. Compressive fatigue damage and failure mechanism of fiber reinforced cementitious material with high ductility. Cem Concr Res 2016;90:174–83. https://doi.org/10.1016/J.CEMCONRES.2016.09.019.

[22] Vicente MA, Mínguez J, González DC. Computed tomography scanning of the internal microstructure, crack mechanisms, and structural behavior of fiber-reinforced concrete under static and cyclic bending tests. Int J Fatigue 2019;121:9–19. https://doi.org/10.1016/J.IJFATIGUE.2018.11.023.

[23] Heirman G, Vandewalle L. The influence of fillers on the properties of self-compacting concrete in fresh and hardened state. Proc. 3rd Int. Symp. Self-Compacting Concr., RILEM Publications SARL; Bagneux; 2003, p. 606–18.

[24] Kanellopoulos A, Savva P, Petrou MF, Ioannou I, Pantazopoulou S. Assessing the quality of concrete – reinforcement interface in Self Compacting Concrete. Constr Build Mater 2020;240:117933. https://doi.org/10.1016/j.conbuildmat.2019.117933.

[25] Diego Carro-López BG-F. Dosificación, propiedades en estado fresco y reología de hormigón autocompactante con áridos reciclados finos. Hormigón y Acero 2018;69.

[26] Alyamac KE, Ghafari E, Ince R. Development of eco-efficient self-compacting concrete with waste marble powder using the response surface method. J Clean Prod 2017;144:192–202. https://doi.org/10.1016/j.jclepro.2016.12.156.

[27] Sainz-Aja JAA, Carrascal IAA, Polanco JAA, Sosa I, Thomas C, Casado J, et al. Determination of the optimum amount of superplasticizer additive for self-compacting concrete. Appl Sci 2020;10. https://doi.org/10.3390/app10093096.

[28] Sosa I, Thomas C, Polanco JA, Setién J, Tamayo P. High Performance Self-Compacting Concrete with Electric Arc Furnace Slag Aggregate and Cupola Slag Powder. Appl Sci 2020;10:773.

[29] 12350-8:2010 EN. Testing fresh concrete - Part 8: Self-compacting concrete - Slump-flow test 2011.

[30] AENOR. EN 12350-2 "Testing fresh concrete - Part 2: Slump-test" 2009.

[31] CEN. EN-12390-3/AC Testing hardened concrete - Part 3: Compressive strength of test specimens 2009.

[32] CEN. EN-12390-13 Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression 2014.

[33] Sainz-aja J, Thomas C, Carrascal I, Polanco JA, Brito J De. Fast fatigue method for self-compacting recycled aggregate concrete characterization. J Clean Prod 2020:123263. https://doi.org/10.1016/j.jclepro.2020.123263.

[34] Gutiérrez-Solana F, Cicero S. FITNET FFS procedure: A unified European procedure for structural integrity assessment. Eng Fail Anal 2009;16:559–77. https://doi.org/https://doi.org/10.1016/j.engfailanal.2008.02.007.

[35] Cicero S, Gutiérrez-Solana F, Álvarez JA, Sánchez L. Failure analysis of a hip implant by using the FITNET fitness for service procedure. Eng Fract Mech 2007;74:688–702. https://doi.org/https://doi.org/10.1016/j.engfracmech.2006.06.020.

[36] Gordon JR. A review of fracture assessment procedures and their applicability to welded structures. Can Metall Q 1993;32:195–203.