Cement and Concrete Composites 125 (2022) 104309

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Effect of temperature on fatigue behaviour of self-compacting recycled aggregate concrete

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ARTICLE INFO

Keywords:
Recycled concrete
Fatigue
Temperature
Creep
Self-compacting concrete

ABSTRACT

The most recommendable frequency range for concrete fatigue tests is between 1 and 15 Hz. It has been clearly established that performing the tests at low frequency (<1 Hz) reduces the fatigue limit because it increases test time and therefore, creep damage. On the other hand, there are not enough studies analysing tests above 15 Hz, which could greatly reduce test time. In this work, three recycled concretes were characterized, starting with the comparison between tests at moderate frequency (10 Hz) with tests at very high frequency (90 Hz). From these tests it was observed that, in all cases, the fatigue limit or fatigue life was notably lower in the case of performing the tests at high frequency. The test results show that, in the case of tests performed over the fatigue limit, the temperature of the specimens rises up to approximately 100 °C, while, in the case of tests performed with strength lower the fatigue limit, the temperature stabilises at around 65 °C. In order to analyse whether the temperature was the cause of the reduction in the fatigue limit, creep tests were carried out at 3 temperatures: 20, 65 and 100 °C, and it was possible to verify that creep damage became significantly greater as temperature was increased, and that this effect was emphasized in those cases where the concretes were made with recycled crushed concrete aggregates.

1. Introduction

The large volume of waste generated from both construction and demolition makes it imperative to search for a use for this waste, otherwise this large volume of waste will exhaust landfills in an excessively short time [1]. One of the most commonly used applications is to valorise this waste as recycled aggregates for the manufacture of concrete [2,3]. This not only avoids sending this waste to landfill, but also avoids the extraction of raw materials from quarries, thus favouring the circular economy. This proposal for the recovery of waste generated in construction and demolition is supported by a large number of research projects that guarantee that recycled aggregate concrete (RAC) can be designed with good mechanical and durability properties [4–6]. In addition, several authors have highlighted the benefits of these self-compacting RACs, since they reduce the loss of properties inherent to RAC, and also provide an environmental benefit [4,7,8].

Among the properties of concrete, fatigue behaviour is not a widely studied field, since concrete structures are not generally subjected to this type of load, although it is common to perform fatigue analyses on certain concrete elements, such as railway superstructure elements [9,10], bridges or offshore structures [11–13]. For this type of elements, scientific publications can be found analysing this behaviour, both under bending and compressive fatigue and assessing the influence of the different variables involved in a fatigue test. The effect of fatigue on RAC has also been studied [11,14–17] by analysing both fatigue characterization methods and the influence of the test frequency [18]. It was concluded that the presence of recycled aggregates from crushed concrete reduces the fatigue limit of concrete. Similarly, in the literature cases can be found in which it is noted that for concrete, the test frequency has some influence on the fatigue limit, defining as acceptable test frequencies in the range 1–15 Hz [19–21]. This is important because, as the mean load test level is never 0, the damage comes from a combination of fatigue damage and creep damage, the latter being closely related to the test frequency.

Until now, the study of the effect of temperature on concrete has focused almost exclusively on analysing the effect on concrete that has been previously exposed to high temperatures as a result of a fire. In general, it is indicated that up to 180 °C, no modifications are observed, if the concrete has reached the 180–300 °C range, there is no important modification of its properties, and from 400 °C, it is considered severe

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https://doi.org/10.1016/j.cemconcomp.2021.104309
Received 19 June 2020; Received in revised form 10 September 2021; Accepted 10 October 2021
Available online 16 October 2021

[22–24]. Very few research papers evaluate the mechanical behaviour of concrete at temperatures between 20 and 100 °C. Xiao et al. [25] analysed the effect of strain rate on compressive behaviour of high-strength concrete after exposure to elevated temperatures concluding that the higher the temperature and strain rate are, the larger the number of cracks and fragments will be. Gibson et al. [26] tried to develop a tool based on remote sensing technologies capable of improve databases on historic fire occurrence, location and extent. Xiao et al. [27] studied the shear transfer process across a crack in high-strength concrete after elevated temperatures. Zdenek et al. [28] state that transitional thermal creep, i.e., the transient creep, increases due to temperature change below 100 °C. Otto et al. [29] analysed the temperature increase that occurs during a fatigue test in the moderate frequency range and its impact on the fatigue limit. Nowadays, there are a large number of structures in different industries that work at temperatures above the usual ambient temperature. For this reason, it is especially important to carry out a study that analyses the behaviour of concrete when it is working at this temperature.

In this paper, fatigue tests at moderate frequency (10 Hz) and very high frequency (90 Hz) were performed on three types of recycled concrete. After these tests, tests were carried out above and below the fatigue limit, analysing not only the fatigue limit but also recording the evolution of strain and temperature throughout the test. A moderate frequency test was also carried out in which the evolution of temperature throughout the test was recorded. As these fatigue tests are a combination of fatigue and creep, creep tests were also carried out at 3 different temperatures: 20, 65 and 100 °C. The value of 65 °C was chosen because the temperature of the very high frequency fatigue tests below the fatigue limit stabilized around 65 °C, while the value of 100 °C was selected because the specimens tested above the fatigue limit reached that temperature before breaking.

2. Materials

2.1. Aggregates

For the manufacture of the three self-compacting recycled concretes the recycled aggregates come from two different out-of-service railways superstructure elements, ballast (RA-B) and sleepers (RC-S). From each of them, the particles were divided into three granulometric fractions, coarse aggregates (5–12 mm), a large sand (2–5 mm) and a fine sand (0–2 mm). Table 1 shows the density of each granulometric fraction. Fig. 1 shows the grading curves of each component.

2.2. Cement

A CEM IV (V) 32.5 N type cement according to EN 197-1 [30] was used to manufacture the self-compacting RAC. This cement was used because it contains a high replacement of clinker by fly ash so it directly provides the fine particles which a self-compacting concrete requires. Table 2 shows the cement's chemical composition by fluorescence. The density of this cement according to EN 80103 [31] is 2.85 g/cm^3.

Table 1
Aggregate properties.

Code	Description	Density (g/cm^3)	Absorption (%)
RA-B-CA	Ballast coarse aggregate (5–12)	2.57	1.90
RA-B-LS	Ballast large sand (2–5)	2.74	1.60
RA-B-FS	Ballast fine sand (0–2)	2.82	0.11
RA-S-CA	Sleeper coarse aggregate (5–12)	2.38	5.10
RA-S-LS	Sleeper large sand (2–5)	2.45	4.90
RA-S-FS	Sleeper fine sand (0–2)	2.51	3.45

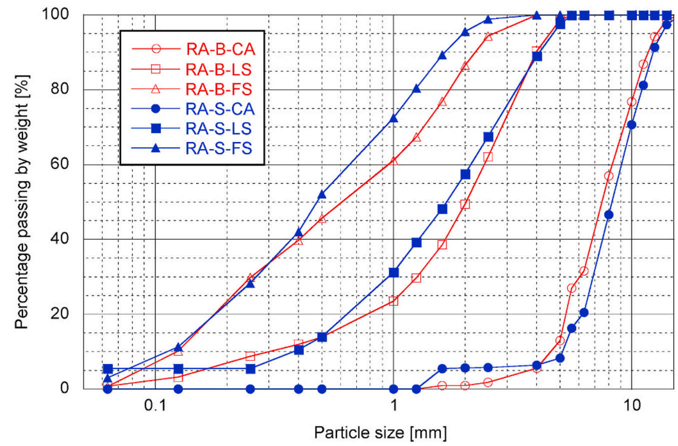


Fig. 1. Aggregate grading curves.

Table 2
Cement chemical composition.

Composition (% wt.)								
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Ignition loss
CEM IV	35.5	41.2	13.3	4.4	1.2	1.3	1.4	1.7

2.3. Concrete

Table 3 shows the mix proportions of three different concretes. The first one, RC-B, is made with RA-B exclusively, the second one, RC-S, is made with RA-S, and the third, RC-M, is a combination of the other two concretes, 6/7 of RC-B and 1/7 of RC-S. These proportions were chosen based on the proportions of ballast and sleepers recovered from the track and waste generation. Note that the w/c ratio of the RC-B is higher although the RA-B shows lower absorption than RA-S. The RC-S demands more water due it's absorption at the same time than the RC-B demands higher quantities of water because of an aggregate higher flakiness index, and a higher volume of cement paste and water is needed to obtain same self-compacting fluidity. Table 3 shows the compressive strength and Young's modulus of the concretes at 90 days, when fatigue and creep tests were performed. Compressive strength and Young's modulus were the mechanical properties analysed. The

Table 3
Mix proportions (kg/m^3).

Material	RC-B	RC-S	RC-M
RA-B-FS	790	–	677
RA-B-LS	320	–	274
RA-BCA	522	–	447
RA-S-FS	–	690	98
RA-S-LS	–	283	40
RA-S-CA	–	587	83
Cement	500	500	500
Water	225	200	221
Superplasticizer additive	10	10	10
Water/cement ratio	0.45	0.40	0.44
% superplasticizer additive/cement	2.00	2.00	2.00
Compressive strength (90 days) (MPa)	59.4	77.8	62.8
Young's modulus (90 days) (GPa)	33.4	33.2	32.2
Slump flow test (mm)	700	730	800
T50cm test (s)	2	2.5	2
L-box test method	0.90	0.90	0.95
V funnel test (s)	7.5	13.5	6.0
GTM stability test (%)	1.0	8.8	8.8
Fresh density (g/cm^3)	2.4	2.3	2.4

compressive strength was determined according to the EN 12390-3 and EN 13290-3/AC [32] and Young's modulus according to EN 12390-13 [33]. Compressive strength was determined at the ages of 7, 28, 90 and 180 days using cubic specimens. Young's modulus was determined at the same ages as the compressive strength but using cylindrical specimens.

The criterion to determine the mix proportions was to obtain the same workability in the three concretes, for this reason, in the case of RC-B, it was necessary to increase the water/cement (w/c) ratio [34].

The mechanical properties tested at different ages during this study are shown in Table 4.

It can be seen that the concrete with the highest values of compressive strength is RC-S, which shows the great effect of a lower w/c ratio, enabling greater values of compressive strength to be obtained than RC-B or RC-M despite having aggregates with worse mechanical properties. The effect of fly ash can also be appreciated, since it increases in the mechanical properties found after 28 days. It should also be noted that these are higher compressive strength values than usual in the case of recycled concrete, which is possible due to the restrictive demands made on the elements of the railway superstructure that have been crushed to obtain the recycled aggregates used. As Tabsh et al. [35] state, there is a correlation between the quality of the parent concrete and the quality of RA. With respect to the Young's modulus, RC-B has the highest value, which is due to the higher stiffness of the aggregates from crushed ballast than those from crushed sleepers [34].

3. Methods

3.1. Fatigue tests

The influence of increasing the frequency up to ≈90 Hz was analysed by Sainz-Aja et al. [22] concluding that increasing the frequency of the fatigue tests produced a reduction in fatigue life of up to 15%. To understand the reason for this reduction in fatigue life, an extensive experimental fatigue test campaign was carried out on the 3 types of self-compacting recycled concrete. This experimental campaign was divided in 3 phases; the first one, comparison of the concrete fatigue behaviour at very high frequency and moderate frequency, the second, evaluation of the fatigue behaviour of concrete near the fatigue limit, and finally, the third, analysing the evolution of temperature during the moderate frequency test.

In all cases, 100 mm diameter, 200 mm high cylindrical specimens were used for the fatigue tests. The ages of all samples were above 90 days, after which it can be considered that the mechanical properties of the concrete are constant. In addition, to analyse the evolution of the specimens during the test, in all cases, the strain state of the specimens was determined by means of two strain gauges on diametrically opposed generatrixes.

In the first phase, the Locati method was followed, with $2{\cdot}10^5$ cycles per step at very high frequency (≈90 Hz) and a moderate frequency (10 Hz). The very high frequency was achieved as the tests were performed on a resonant fatigue machine. The resonance frequency of the test machine and the test specimens used were ≈90 Hz. The Locati method attempts to estimate the fatigue limit of an element by means of a single test. This methodology consists of applying increasing load steps until failure occurs [36,37]. The load values of each of these steps are shown in Table 5. To determine these load steps, maximum load was defined as the product of one parameter (k) times the compressive strength of each material. A stress ratio of 0.1 was used throughout all the tests. The procedure followed to determine the fatigue limit of the 3 self-compacting RACs from the Locati tests was that proposed by Thomas et al. [14] who defined the fatigue limit as 80% of the stress range during the breaking step.

In the second phase, a fatigue test was performed with $2{\cdot}10^6$ cycles at load values corresponding to the step below and above the fatigue limit. These tests were also performed at very high frequency. In these tests, in addition to recording the evolution of the strain during the test, the temperature of the external face of the specimen was also recorded by mean of a thermographic camera.

Finally, in the third phase, the Locati tests at low frequency were repeated, the only difference was that now the temperature during the whole test was registered in the same way as in the second phase.

During the analysis of the fatigue limit of each concrete two different parameters were analysed, the fatigue limit, which is a stress range ($\boldsymbol{\Delta\sigma_{FL}}$) and the ratio between the fatigue limit and the compressive strength ($\boldsymbol{\Delta\sigma_{FL'}}$).

3.2. Creep at different temperatures

It is concluded that in the case of compressive fatigue the damage is a combination of fatigue damage and creep damage. This is an unexpected result, never observed before and may be of great interest. For this reason, it was decided to perform creep tests at 3 different temperatures; firstly, at environmental temperature (20 °C); secondly, at 65 °C, which is the temperature registered in the specimens in the test performed below the fatigue limit and, finally, at 100 °C, which is the temperature recorded as being reached by the specimens tested above the fatigue limit. In these tests, 1 h before starting, the specimens were placed in an oven at the target temperature, after which the creep test was started without removing the specimen from the oven, see Fig. 2.

These creep tests were similar to the Locati method, which consists of applying steps of increasing load. These load steps coincide with the mean value and duration of the steps of the Locati tests at moderate frequency.

4. Results

4.1. Moderate vs. very high frequency fatigue

Fig. 3 shows 3 self-compacting RAC strain evolution during the first phase tests at very high frequency (≈90 Hz) and moderate frequency (10 Hz).

As can be appreciated in Fig. 3, in the first part of test for each of the RAC, tests at very high and moderate frequencies provided similar strain values. After this initial part, the curves began to diverge; in all cases the very high frequency strain values were greater than the moderate frequency ones, until the specimens broke.

Fig. 4 shows a comparison between the fatigue limit obtained at very high frequency and at moderate frequency. In this case, contrary to what is stated by other authors, "An increase in the loading frequency leads to a higher number of load cycles to failure" [38], an increase in the frequency, very high in our case, reduces the fatigue limit or the fatigue life of the concrete.

From Fig. 4, it can be seen that in all cases the fatigue limit is higher when the test is performed at moderate frequency, moreover, it can be seen that this effect is magnified in the case of the RC-S and that there is a correlation between both methodologies. Fig. 5 shows that the RC-S have the lowest fatigue limit/compressive strength ratio. The two types of aggregates are of very high quality, both from ballast and

Table 4
Mechanical properties.

Property	Age (days)	RC-B	RC-S	RC-M
Compressive strength (MPa)	7	32.5	41.9	37.6
	28	49.4	57.2	52.6
	90	59.4	77.8	62.8
	180	66.2	82.3	70.4
Young's modulus (GPa)	7	26.4	26.1	25.5
	28	30.5	28.9	31.6
	90	33.4	33.2	32.2
	180	35.3	34	35.2

Table 5
Fatigue test stress scenarios.

k	RC-B			RC-S			RC-M		
	σ_{Max} (MPa)	σ_{Min} (MPa)	$\Delta\sigma$ (MPa)	σ_{Max} (MPa)	σ_{Min} (MPa)	$\Delta\sigma$ (MPa)	σ_{Max} (MPa)	σ_{Min} (MPa)	$\Delta\sigma$ (MPa)
0.30	17.8	1.8	16.0	23.3	2.3	21.0	18.9	1.9	17.0
0.35	20.8	2.1	18.7	27.2	2.7	24.5	22.0	2.2	19.8
0.40	23.8	2.4	21.4	31.1	3.1	28.0	25.1	2.5	22.6
0.45	26.7	2.7	24.0	35.0	3.5	31.5	28.3	2.8	25.5
0.50	29.7	3.0	26.7	38.9	3.9	35.0	31.4	3.1	28.3
0.55	32.7	3.3	29.4	42.8	4.3	38.5	34.6	3.5	31.1
0.60	35.7	3.6	32.1	46.7	4.7	42.0	37.7	3.8	33.9
0.65	38.6	3.9	34.7	50.6	5.1	45.5	40.8	4.1	36.7
0.70	41.6	4.2	37.4	54.5	5.4	49.1	44.0	4.4	39.6

Fig. 2. Creep test assembly.

crushed sleepers, which gives better fatigue results than in the case of other recycled concretes. However, despite being high quality recycled aggregates, the production process of these aggregates causes micro-cracks, which under the effect of cyclic loads grow and cause the premature failure of the specimens. This effect has been observed by other authors [39–41].

It can be deduced that during the trials there is a phenomenon that evolves differently in the tests at very high and moderate frequency and this is the reason why different results are obtained at high and low frequency. This hypothesis is supported by the observation that, as previously stated, in the first part, moderate and very high frequency curves show similar behaviour and, with the passing cycles, the behaviour begins to diverge. It was also observed that in the high-frequency tests higher deformation values are obtained than expected for concrete. For those reasons, it was decided to carry out fatigue tests both above and below the fatigue limit at very high frequency to explore the phenomenon that modifies the behaviour of the concrete.

Fig. 5 shows the results of testing both above and below the fatigue limit of each of the three self-compacting RACs designed for this study. From each of these tests, both the evolution of the strain and the temperature during the test are shown.

From Fig. 5, if the evolution of the strain is analysed, it can be seen

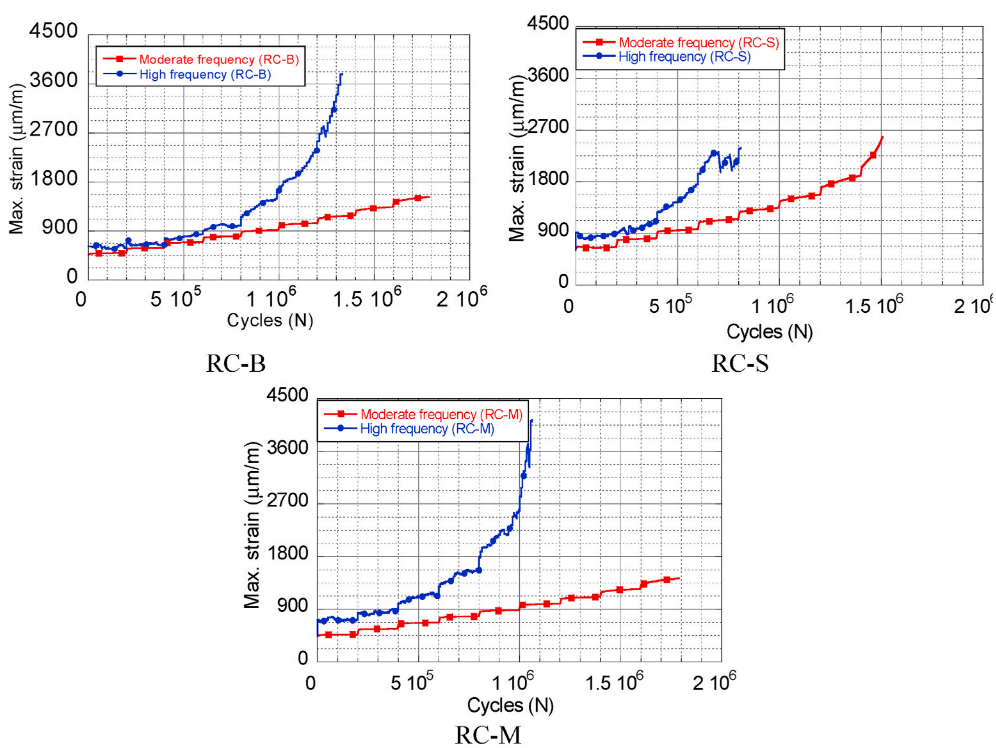


Fig. 3. Strain evolution during moderate and high-frequency Locati test.

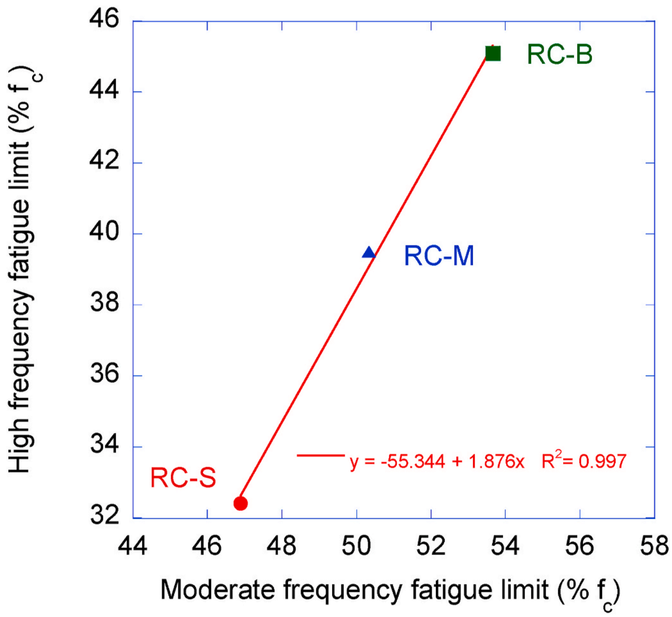


Fig. 4. Comparison of the fatigue limit obtained at high and moderate frequency.

that, in the case of tests below the fatigue limit, the strain values are almost stable from the beginning of the test, while in the tests above the fatigue limit, in a first zone it seems to be approximately stable, while, at a certain point, values begin to grow exponentially until the breakage of the specimen occurs. A similar situation can be observed with regard to temperature. In the case of specimens tested below the fatigue limit, the temperature stabilises, while in those tested above the fatigue limit, the temperature increases throughout the test. If we analyse the temperature values for which this variation in strain evolution is experienced, we can see that in all cases they are between 60 and 70 °C, a temperature range that coincides with the temperature at which the tested specimens are kept below the fatigue limit. As no reference has been found in the literature indicating that a fatigue test can reach such temperature increases, it was postulated that this was an effect of high frequency. To validate this hypothesis, a fatigue test was performed at a moderate frequency in which the evolution of temperature throughout the test was recorded. Fig. 6 shows the evolution of temperature during a moderate frequency Locati test. It can be seen that, even when the specimen is close to breaking, it has not reached 40 °C.

This increase in the temperature of the specimen throughout the test is justified because, during the loading cycles applied, there is a relative displacement between the faces in contact of cracks inherent to concrete, which produces a certain amount of friction and therefore generates heat, and as concrete is a material with a high thermal inertia, it is not capable of dissipating this energy to the outside. Performing these

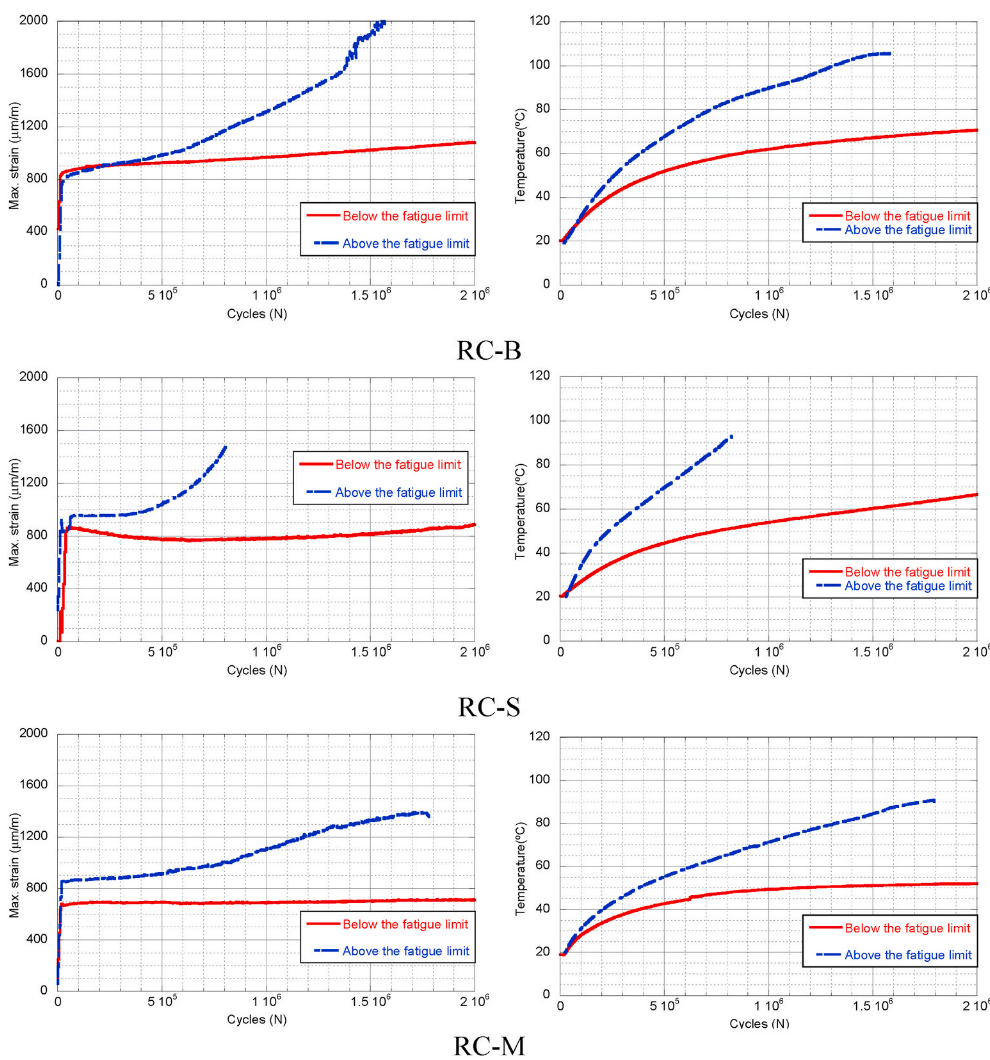


Fig. 5. Evolution of max. strain and max. temperature during a high-frequency test.

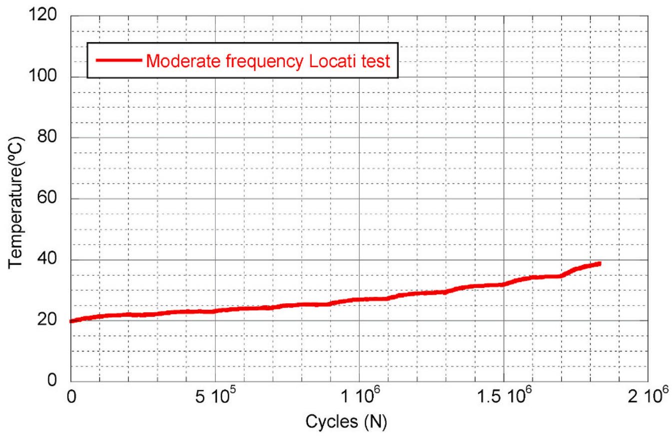


Fig. 6. Evolution of the temperature during a moderate frequency Locati test.

tests at very high frequency reduces the time between cycles, which means that the amount of heat dissipated per cycle is lower and, therefore, the specimens increase their temperature more quickly than in the case of testing at moderate frequency.

Fig. 7 shows an example of temperature distribution recorded by the thermographic camera for the same fatigue test at high frequency (a) and moderate frequency (b) just before the specimen failure. In this figure it can be seen that just before the failure of the specimens, the temperature rose to about 93 °C in the case of high frequency and about 38 °C in the case of moderate frequency. Moreover, it can be seen that the distribution is not totally homogeneous, it can be seen that the temperature is higher in the upper part of the specimen than in the lower part.

4.2. Creep test

Once it was demonstrated that performing fatigue tests on concrete at a very high frequency increases the temperature of the concrete, the influence of this increase in temperature on the mechanical behaviour of the concrete was analysed. To do this, given that it is compressive fatigue, and therefore the damage suffered by the element is a combination of fatigue damage and creep damage, the evolution of the strain undergone by concrete specimens subjected to constant loads was analysed, specifically the load values corresponding to the mean values of the steps in the Locati tests. In Fig. 8 to Fig. 10, the strain evolution during the creep tests is shown at the 3 temperatures (see Fig. 9).

From Figs. 8–10 it can be seen that temperature has a great effect on concrete strain. In all cases, the temperature is increased from 20 to 65 °C and the concrete becomes more deformable. In the last steps of the test, an increase was found of 17, 58 and 28% for RC-B, RC-s and RC-M respectively. The case in which this is most pronounced is in the RC-S, which, contains exclusively recycled aggregates from crushed concrete sleepers. In the case of increasing the temperature from 20 to 100 °C, for

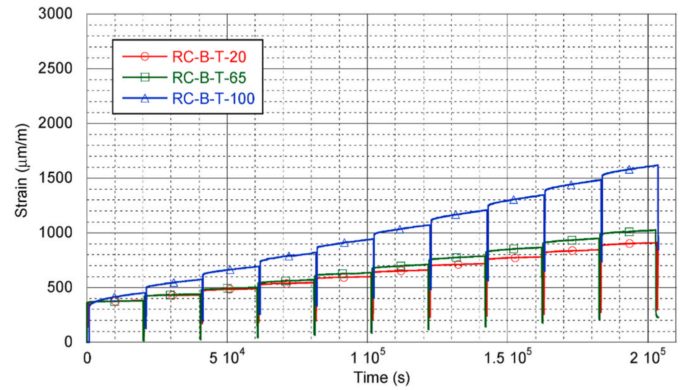


Fig. 8. Strain evolution during creep tests on RC-B at different temperatures.

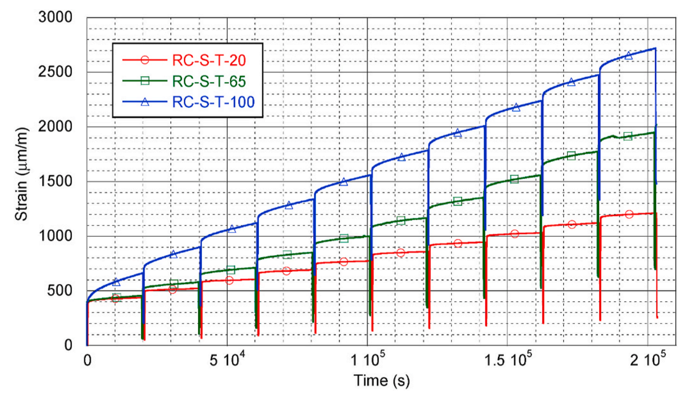


Fig. 9. Strain evolution during creep tests on RC-S at different temperatures.

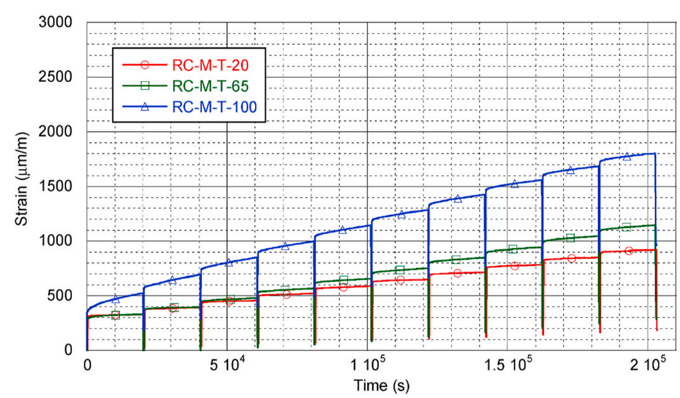
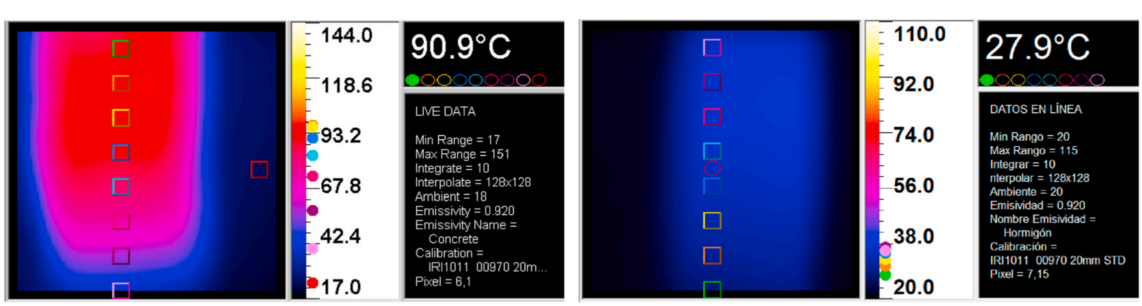


Fig. 10. Strain evolution during creep tests on RC-M at different temperatures.



(a) High frequency (b) Moderate frequency

Fig. 7. Temperature distribution on a sample during fatigue test.

the last steps, the increase is 78, 125 and 100% for RC-B, RC-S and RC-M respectively, in this case RC-S also undergoing the greatest increase. From these values, it can be seen that the more the temperature increases, the greater is the effect of temperature, since the values obtained at 65 °C are closer to those obtained at 20 °C despite the difference in temperature being greater between 20 and 65 °C than between 65 and 100 °C. When comparing the results of strain in the last steps for the same temperatures but different types of concrete, it can be seen that the one with the greatest influence of creep is RC-S, while RC-B is the least influenced and in all cases RC-M is in an intermediate situation. In particular, it can be seen that the ratio between the strain values for the same steps and same temperature, but different concrete, remains approximately constant. The average value for the case of RC-S/RC-B is 1.57 ± 0.24, for the case of RC-S/RC-M it is 1.49 ± 0.16 and for the case of RC-M/RC-B it is 1.06 ± 0.06. These values are in line with the values provided by Geng et al. [42] who found that after 8 months under sustained loading, the creep deformation of RAC can be 50–120% higher than that experienced by the counterpart NAC. Several authors have found that the effect of creep is greater in the case of recycled aggregate concrete elements than in case of natural aggregate concrete due to the presence of attached mortar in the recycled aggregates [42,43]. Therefore, the studied concretes are more susceptible to creep due to the higher amount of paste present in self-compacting concrete comparing with conventional concretes. In this research, the RC-S is the one with the highest amount of mortar and is the concrete that suffers the most creep damage.

It seems that this strain increase is due to the mortar not the aggregates. Under this assumption, it can be justified that the fatigue limit of concrete at very high frequency is lower than at moderate frequency. The relative displacements between aggregate and paste will be higher and, therefore, the growth of the cracks present in the past-aggregate interphase will be faster. In addition, several authors using micro-CT techniques have concluded that the micromechanism of damage that produces fatigue failure is the growth of cracks in the past-aggregate interface [13,44].

5. Conclusions

When a concrete element is subjected to fatigue, in almost all cases it is a case of fatigue in which the mean load value is not 0, so the concrete damage is a combination of creep and fatigue. An element may be designed considering fatigue, but as there is a combination of fatigue and creep damage, the boundary conditions may magnify the creep damage and, therefore, reduce the fatigue limit significantly. In this paper, it has been shown that temperature increases above 65 °C can significantly magnify creep damage and that these temperatures can be caused by an excessively high test frequency.

It was observed that the specimens tested at very high frequency below the fatigue limit reach a temperature close to 65 °C, after which the temperature stabilized. In addition, in very high-frequency tests above the fatigue limit, the temperature increased to approximately 100 °C, at which point specimen failure occurred.

It was shown that the effect of maintaining a constant load on a specimen above 65 °C has a magnified effect with respect to the effect at ambient temperature, in the case of increasing the temperature from 20 to 100 °C, it causes the strain to double. This explains the premature failure of specimens tested at very high frequency compared to those tested at ambient temperature, as the latter have undergone a significant temperature increase.

Good practice would imply that fatigue tests on concrete should be carried out at a frequency of between 1 and 15 Hz. It should be noted that, although this is a good option for comparing the results obtained for different concretes, it is the situation in which the fatigue limit of the concrete is maximized, so it entails some uncertainty. For this reason, specific creep studies should be carried out when the structure in question is subjected to either a high mean level of loads or temperatures above 65 °C.

At present, some structures are designed without considering the effect of temperature on creep damage, which reduces the existing safety coefficient. It is therefore essential to extend the analysis of the influence of temperature on the mechanical properties of concrete elements in order to avoid accidents. In addition, existing industrial structures can be found working in the temperature range in which a severe modification of the properties of concrete has been found (>60 °C), so the importance of anticipating their failure is magnified.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the Spanish Ministry of Economy and Competitiveness of Spain for financing the project MAT2014-57544-R. Also, authors would like to thank to the LADICIM, Laboratory of Materials Science and Engineering of the University of Cantabria for making available to the authors the facilities used in this research. The authors would like to thank the “Augusto Gonzalez Linares” post-doctoral grant program of the University of Cantabria for their support.

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