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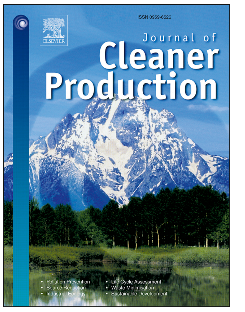

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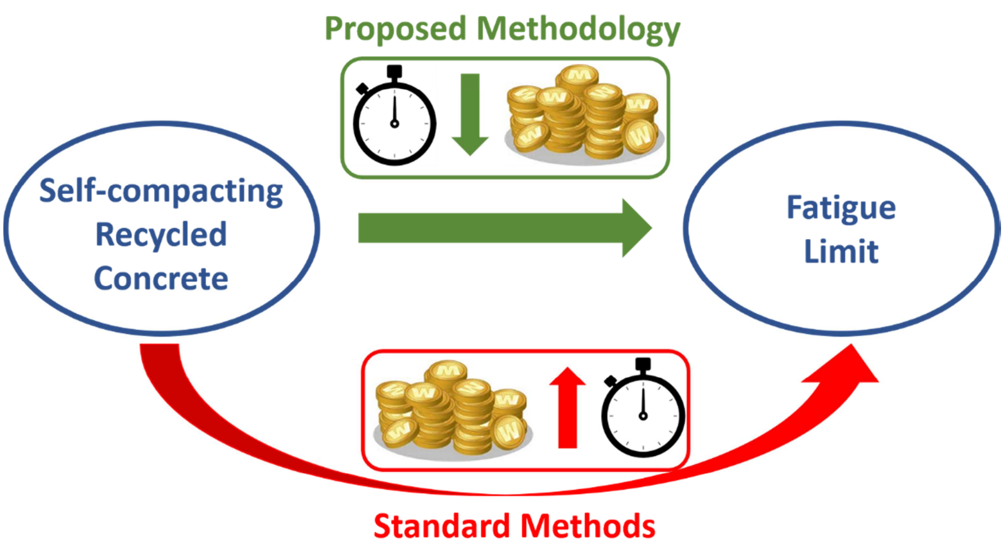
Abstract:

Designing or analysing the influence of fatigue on concrete structures is becoming increasingly important for a number of structural elements. For this reason, it is necessary to define a method capable of determining the concrete's fatigue limit in the most economical, fast and efficient way. The aim of this study is to compare and correlate different methods found in the literature in order to reduce the number and duration of the tests required to determine the fatigue limit. This reduction will consequently reduce the economic costs of determining the fatigue limit. For these proposes three different types of self-compacting recycled concrete was used. A linear correlation was found between the analysed methods, which means that the methods are capable of providing similar results and that the results obtained by the economical procedure must be selected. This work opens the door to define an optimal procedure in the process of concrete fatigue characterization, which is capable of yielding results up to five times faster and more economical **than with other methodologies,** so that resources are not wasted.

Keywords: resonance frequency; recycled aggregate; recycled aggregate concrete; fatigue; Locati; Staircase; self-compacting



Highlights:

- Locati and Staircase method provide similar fatigue limit in high frequency fatigue;
- A drop in the resonance frequency means an increased damage;
- 2×105 cycles per Locati step are enough to determine the fatigue limit.

1. Introduction

Concrete is the material most used in construction sector. In addition, approximately 10% of man-made CO_2 emissions are from concrete production and transportation (Sainz-Aja et al., 2020) and, for this reason, there are numerous studies that seek ways to reduce concrete's environmental impact. Naseri et al. (2020) developed a new machine learning technique to design sustainable concrete mixes. Zhao et al. (2020) used a ternary diagram to compare traditional concrete with three kinds of green concrete: recycled aggregate concrete production mode, fly ash concrete production mode, and circular economy concrete production mode, the importance of the circular economy is highlighted by other authors such as Maroušek et al. (2019). Opon and Henry (2019) defined a new indicator to quantify the sustainability of concrete. This new indicator considers the pillars of sustainability (environment, economy and society) and the sustainable development goal. Marvila et al. (2019) checked the possibility of total replacing all or at least a part of hydrated lime with marble waste. Azevedo et al. (2020) evaluated a new process methodology trying to incorporate primary pulp and paper industry sludge waste into cement and lime-base mortars. But, nowadays, the most popular way to try to reduce concrete environmental impact is to use recycled aggregates (RA) instead of natural aggregates.

It has been widely established that the use of RA is a necessity nowadays because of the large amount of waste going to landfill every day (Poon and Chan, 2007). This environmental concern is mitigated by ensuring that these wastes can generate concrete with both good mechanical (Thomas et al., 2013) and durability (Thomas et al., 2013) properties.

While the fatigue behaviour of structural metal elements is commonly studied, in the case of concrete elements it is not so common. Although it is not usual to carry out a fatigue characterisation of concrete elements, there are some elements that are subject to highly variable significant loads that make it necessary to perform fatigue characterisation. Examples of this type of elements include: offshore structures subject to variable wind, waves and tidal loads (Xiao et al., 2013), rail and road bridges (Alliche, 2004), railway superstructures, sleepers (Ferreño et al., 2019) or slab tracks (Sainz-Aja et al., 2020) and/or wind generators (Skarżyński et al., 2019). This is why several authors have performed studies that analyse the fatigue behaviour of concrete at the microstructural level by means of tomographic analysis (Thomas et al., 2019, 2018), even establishing the concrete fatigue micro-mechanisms that produce concrete failure with recycled (Sainz-Aja et al., 2019a) and natural aggregates (Skarżyński et al., 2019), Thomas et al. (2014) determined the fatigue limit under compression of 24 mix proportions of RAC. Xiao et al. (2013) analyzed the effect of compressive and bending fatigue of recycled aggregate concrete. Li et al. (2016) analyzed the compressive fatigue behavior of fiber reinforced cementitious materials. Vicente et al. (2019) analyzed the bending fatigue using computed tomography scanning. From these studies, it was possible to define the damage procedure undergone by concrete until its failure. This process begins with the onset of cracks in the interfacial transition zone (ITZ). Subsequently, these cracks begin to grow and interconnect until they reach a critical dimension that leads to failure (Carloni and Subramaniam, 2013). Regarding the fatigue behaviour of recycled concrete, although it is not a very developed topic, there are some works that indicate that the use of recycled concrete aggregates reduces the fatigue life, especially at replacements greater than 20% (Luo and Yao, 2011). Thomas et al. (2014) determined that the loos in the fatigue limit due to the presence of recycled aggregates is higher than the reduction in the compressive strength. Also, Thomas et al. (2014) found that the effect of the recycled aggregate on the concrete dynamic response depends not only on the quality of the recycled aggregate but also the new concrete quality.

Strength-Number of cycles' (S-N) curves are the most common way of analysing fatigue behaviour. Moreover, this is the method proposed by Eurocode 2 (British Standards Institution, 2015). However, the problem with this methodology is that it requires a large number of long-term tests and specimens, which means both an increase in time and a high economic cost and, in some cases, it is not possible to provide these samples. In addition to the S-N curves, a number of other characterisation techniques that focus on determining the fatigue limit only have been taken into account. Fatigue limit is the threshold stress range below which failure does not occur independently of the number of cycles applied, so that infinite life can be considered in relation to these stress levels. Specifically, the Staircase method has been proposed. This testing methodology is used as a standardized procedure, for e.g. to characterize the fatigue limit in welded rails, according to standard UNE-EN 14587-1 (CEN, 2018). This type of test requires a significantly lower number of tests than those required to determine an S-N curve, but approximately 10 results are still required. In order to shorten the time and lower the economic cost and the number of samples required, another test method, the Locati method, was used (Locati, 1950), which intends to estimate the fatigue limit by means of a single test. A procedure similar to the Locati method is used as a standardized procedure to determine the fatigue limit of railway sleepers (CEN, 2016).

The Locati method has been used by different researchers to determine the fatigue limit, although there is no unanimity in the procedure to determine the fatigue limit of the Locati tests. Kong et al. (2015) analysed the effect of laser quenching on fatigue properties and fracture morphologies of boronized layer on Cr12MoV Steel by Locati method. They determine the fatigue limit by fatigue accumulation damage. Maximov et al. (2017) analysed the effect of slide burnishing on the high-cycle fatigue performance of 2024-T3 high-strength aluminium alloy by the Locati method. The fatigue limit was determined assuming the validity of Palmgren–Miner linear damage hypothesis. Sainz-Aja et al. (2019a) used the Locati method to determine the fatigue failure micro-mechanisms in recycled aggregate mortar combined with μCT analysis. Sainz-Aja et al. (2019c) used the Locati method to determine the fatigue limit of high-frequency tests of recycled aggregate concrete. In this case, the parameter to determine the fatigue limit was a decrease in the fatigue resonance frequency. Casado et al. (2006) used the Locati method to determine the Fatigue failure of short glass fibre reinforced PA 6.6 structural pieces for railway track fasteners. In this case, the fatigue limit was determined based on the strain evolution. Thomas et al. (2014) used the Locati method to determine the recycled aggregate concrete fatigue behaviour. They determined the fatigue limit as a correlation with the maximum load of the Locati tests.

Conventionally, the Staircase method at constant and moderate frequency is the way to determine concrete's fatigue limit, but is it the best way to determine it? The aim of this work is to validate a method to determine the concrete fatigue limit ($\Delta\sigma_{FL}$) and the fatigue limit/compressive strength ratio ($\Delta\sigma_{FL'}$) with the least number of test specimens and in the shortest possible time. For this purpose, the test frequency was increased as much as possible to compare the Staircase and Locati methods and characterize three recycled concrete types. Fatigue tests were performed in a resonance compression fatigue test machine, which performs tests at the resonance frequency of the assembly test machine and specimen, in this case approximately 90 Hz. Regarding the test, the Staircase method was taken as a reference with 2×10^6 cycles per test (Bellido de Luna, 1989), which was compared with Locati tests. As there is no certainty about the number of cycles per step in the Locati method, it was decided to perform it, on the one hand, with 2×10^5 (L2) and, on the other hand, 5×10^5 (L5) cycles per step, thus enabling the analysis of the influence of the number of cycles per step. Finally, the influence of the material was analysed, characterising three types of self-compacting recycled concrete, the first of which made with recycled aggregate from out-of-use railway ballast (RC-B), which is similar to natural aggregate. The second one was made from recycled aggregate from out-of-use railway sleepers (RC-S), i.e. recycled concrete aggregate. The third one contained both types of aggregate, ballast and out-of-use sleepers, in the proportions in which they are found in tracks (RC-M).

In this paper, once the introduction is finished, in the section of Materials and methodology, the materials used in the research, the mix proportions of concrete and the procedures followed to obtain compressive strength, elastic modulus and the three types of fatigue tests carried out are described in detail. The following section, "Results and discussions", is divided into three blocks: results of compressive strength and elastic modulus tests, results of the fatigue tests, and an analysis of the correlation between the different methods used to determine the fatigue limit. Finally, the conclusions obtained from this work are presented.

2. Materials and methodology

The design of experiments proposed for this research begins with the characterization of the aggregates and cement. Afterwards, three mix proportions of recycled self-compacting concrete are defined. Subsequently, the values of compressive strength and elastic modulus are determined, and the fatigue tests end the procedures. These fatigue tests include Staircase tests as Locati tests with 2×105 and 5×105 cycles per step.

2.1. Aggregates

The three self-compacting recycled concrete mixes were manufactured using exclusively recycled aggregates from the valorisation of out-of-service railways superstructure, ballast (RA-B) and sleepers (RA-S). These wastes were crushed and sieved, grouping each of the wastes in three size fractions. Table 1 shows the classification and the relative density of coarse aggregates and the real density of sands. Fig. 1 shows the grading curve of each of the aggregates. Moreover, the flakiness indexes of the coarse aggregates (CA) were: 14 % for RA-B-CA and 5 % for RA-S-CA. The water absorption coefficient of RA-B-CA in 1.9 % and 5.1% wt. for the RA-S-CA.

Table 1: *Aggregate properties.*

Description	Code	Min-Max size (mm)	Density (g/cm³)
Ballast coarse aggregate	RA-B-CA	5-12	2.57
Sleeper coarse aggregate	RA-S-CA	5-12	2.38
Ballast coarse sand	RA-B-LS	2-5	2.74
Sleeper coarse sand	RA-S-LS	2-5	2.45
Ballast fine sand	RA-B-FS	0-2	2.82
Sleeper fine sand	RA-S-FS	0-2	2.51

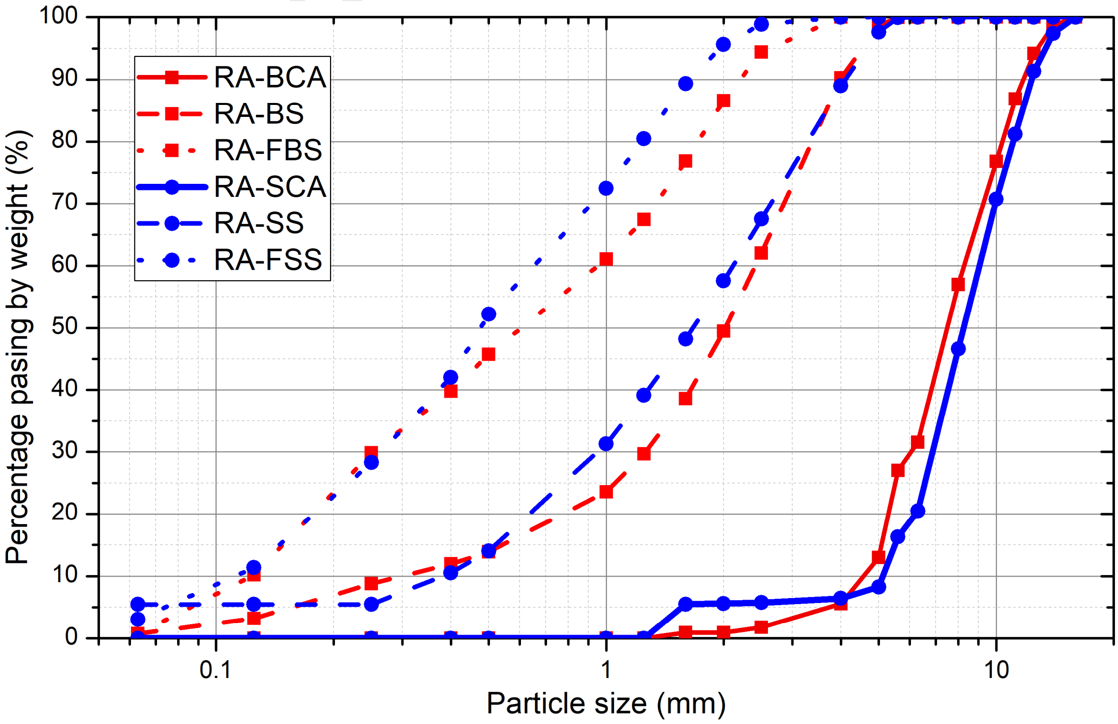


Fig. 1: *Aggregate grading curves. The recycled aggregates from crushed sleepers are represented in blue and the ones from crushed ballast in red.*

2.2. Cement

As a self-compacting concrete needs a high volume of fine particles and the recycled sands were not able to provide this, a CEM IV (V) 32.5 N type cement according to EN 197-1 (CEN, 2011a) was used, which has a high replacement of clinker with fly ash. The density of this cement according to UNE 80103 (CEN, 2013) is 2.85 g/cm^3. The Blaine specific surface is 3885 cm^2/g according to EN 196-6 (CEN and 196-6:2010, 2010). Table 2 shows the cement's chemical composition by fluorescence.

Table 2: *Cement chemical composition.*

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

2.3. Mix proportions

Three concrete mix proportions were designed. The first one, RC-B, used only recycled aggregates from crushed ballast, the second one, RC-S, used exclusively recycled aggregates from out-of-service sleepers, and finally, the third one, RC-M, using both kinds of aggregates in the proportion that they occur in the track, 6/7 of ballast and 1/7 of sleepers. Table 3 shows the three mix proportions.

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

Material	**RC-B**	**RC-S**	**RC-M**
Water	225	200	221
Cement	500	500	500
Superplasticizer additive	10	10	10
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
% sand (0-2 mm) of the total sand	70	70	70
% coarse aggregate of the total aggregates	35	40	36
Water/cement ratio	0.45	0.40	0.44
% superplasticizer additive/cement	2.00	2.00	2.00

The mix proportions were tuned to obtain a similar workability in the three mixes. For this reason, it was necessary to increase the water content of RC-B, due to RA.B's higher flakiness index (Sainz-Aja et al., 2019b). A high content of fine aggregates in the mix proportion was needed to obtain self-compacting features. The superplasticizer admixture used in this work is a polycarboxylic ether type superplasticizer called "MasterGlenium® ACE 450 BASF"

2.4. Mechanical properties

The evolution over time of the two main mechanical properties of concrete, compressive strength and Young´s modulus, was measured. For compressive strength characterization, 100 mm cubes were tested according to the EN 12390-3 and EN 13290-3/AC (CEN, 2011b; CEN et al., 2009) standards at 1, 2, 3, 5, 7, 28, 90 and 180 days. Modulus of elasticity tests were carried out at 7, 28, 90 and 180 days, according to EN 12390-13 (CEN, 2014) and using cylindrical test specimens of 200 mm height and 100 mm diameter. These ages were selected due to they are the usual ages for; 7 days: Date of special interest for formwork removal. 28 days: In conventional concrete, the mechanical properties have reached almost 100 %. 90 days: The presence of fly ash causes important increases of the mechanical properties until this age. 180 days: It is considered that from this age on the gain in mechanical properties, even with the presence of fly ash, will be minimal.

2.5. Fatigue tests

The experimental fatigue campaign was first divided in two kinds of tests, Staircase and Locati. The Locati test was also divided into two new groups depending on the number of cycles per step (**Fig. 2**).

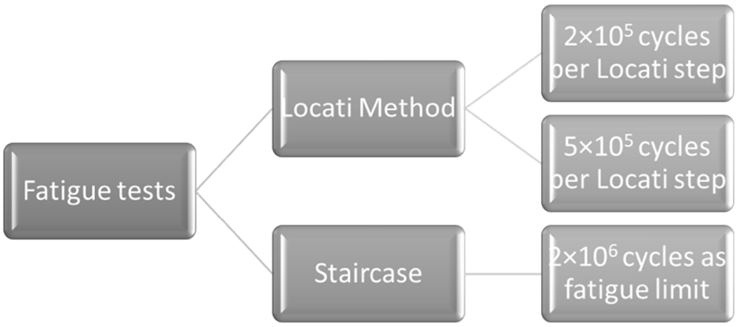


Fig. 2: *Fatigue test scheme carried out throughout the research.*

In all laboratory tests, the strength, specimen strain and resonance frequency of the specimen and test machine assembly are continuously recorded. Specimen strain was recorded by means of two strain gauges attached to two diametrically opposed longitudinal generatrixes. In the case of the Staircase tests, the temperature evolution of the specimen's external surface was also recorded by means of a thermographic camera.

Since both types of test are based on applying loads grouped by steps, the same load steps were used for all tests. To characterize this load scenario, a coefficient (k) was defined as the ratio maximum load in the step/compressive strength at the testing age of 90 days. Moreover, the stress ratio (min. stress/max. stress) was defined as 0.1. Table 5 shows the nine possible load scenarios defined for this test.

The Staircase method is a standardized and proven method, so it was used as a reference method to validate the results obtained by the Locati method. This method consists of applying a fixed number of cycles, in this case $2{\times}10^6$, to a sample with the loads defined in the corresponding step. If the sample breaks, the next sample is tested with the loads of the previous step, while if the sample passes the test, the loads of the next test will be the load corresponding to the next step, see Table 4. Once all the tests had finished, the analysis was done according to the standard (CEN, 2010). This analysis begins by distinguishing between tests passed (1) and non-passing tests (0). The next step is to determine which of the two phenomena is less common, in the example (0). Next, the lowest step in which the less common phenomenon was identified is determined, in the example step 3 marked in grey. This step is defined as the reference step and a value of i=0 is assigned to it. Once the reference step is determined, the variables N, A and B are obtained, where i is the step number with respect to the reference step and N is the number of times the less usual event is repeated in each of these steps, as per Equation 1 to Equation 4.

Table 4: *Staircase tests procedure description.*

Step	Δσ [MPa]	1	2	3	4	5	6	7	8	9	i	n_i	$i \cdot n_i$	$i^2 \cdot n_i$
2	24.5		1				1							
3	28.0	0		1		0		1		1	0	2	0	0
4	31.5				0				0		1	2	2	2
N												4		
A													2	
B														2

$$A = \sum i \cdot n_i \quad \text{Equation 1}$$

$$N = \sum n_i \quad \text{Equation 2}$$

$$B = \sum i^2 \cdot n_i \quad \text{Equation 3}$$

$$\sigma'_{FL} = \sigma_0 + \delta \cdot (\frac{A}{N} \pm 0.5) \quad \text{Equation 4}$$

Once the parameters N, A and B have been determined, using Equation 6 it is possible to determine the fatigue limit of the samples analysed. In Equation 4, σ_0 is the stress range of the reference step, δ is the variation of stress range between successive steps and ± is plus (+), if the less usual event is that it exceeds the step and, less (-), if on the contrary, the less usual event is that it does not exceed the step. The standard deviation (S) is equal to Equation 5 if Equation 7 is met.

$$S = 1.62 \cdot \delta \cdot (\frac{B \cdot N - A^2}{N^2} + 0.029) \quad \text{Equation 5}$$

$$\sigma_{FL} = \sigma_{FL}' \pm S\ (MPa) \quad \text{Equation 6}$$

$$\frac{B \cdot N - A^2}{N^2} > 0.3 \quad \text{Equation 7}$$

Table 5: *Fatigue test stress scenarios.*

		RC-B			RC-S			RC-M		
Step	k	σ_{Max} (MPa)	σ_{Min} (MPa)	Δσ (MPa)	σ_{Max} (MPa)	σ_{Min} (MPa)	Δσ (MPa)	σ_{Max} (MPa)	σ_{Min} (MPa)	Δσ (MPa)
1	0.30	17.8	1.8	16.0	23.3	2.3	21.0	18.9	1.9	17.0
2	0.35	20.8	2.1	18.7	27.2	2.7	24.5	22.0	2.2	19.8
3	0.40	23.8	2.4	21.4	31.1	3.1	28.0	25.1	2.5	22.6
4	0.45	26.7	2.7	24.0	35.0	3.5	31.5	28.3	2.8	25.5
5	0.50	29.7	3.0	26.7	38.9	3.9	35.0	31.4	3.1	28.3
6	0.55	32.7	3.3	29.4	42.8	4.3	38.5	34.6	3.5	31.1
7	0.60	35.7	3.6	32.1	46.7	4.7	42.0	37.7	3.8	33.9
8	0.65	38.6	3.9	34.7	50.6	5.1	45.5	40.8	4.1	36.7
9	0.70	41.6	4.2	37.4	54.5	5.4	49.1	44.0	4.4	39.6

The Locati method seeks to estimate the fatigue limit using a single test specimen, thus reducing the number of tests will reduce the overall cost of the tests. For this purpose, the test procedure consists of applying increasing load steps, with a fixed number of cycles per step, until the specimen breaks. An explanatory diagram can be seen in Fig. 3. In this case, the load steps were defined previously in Table 5 and, as commented upon in the introduction, because there is no standard in which the number of cycles per Locati method step is specified, it was decided to perform and compare L2 and L5. Different authors use different criteria to estimate the fatigue limit through the Locati test (Casado et al., 2006; Kong and Xie, 2015; Maximov et al., 2017; Sainz-Aja et al., 2019a, 2019c; Carlos Thomas et al., 2014). In this situation, to analyse the Locati method, two criteria found in the literature were used: method-1 and method-2. Method-1, proposed by Thomas (2012) in his PhD thesis, defines the fatigue limit as 80% of the stress range of the last step that the specimen withstands. Method-2, proposed by Sainz-Aja (2019) in his PhD thesis, defines the fatigue limit in resonance as the stress range of the step previous to the step in which a fall in resonance frequency of the system is observed.

3. Results and discussions

3.1. Compressive strength and Young's modulus

Table 6 shows the evolution of compressive strength and Young's modulus as a function of time.

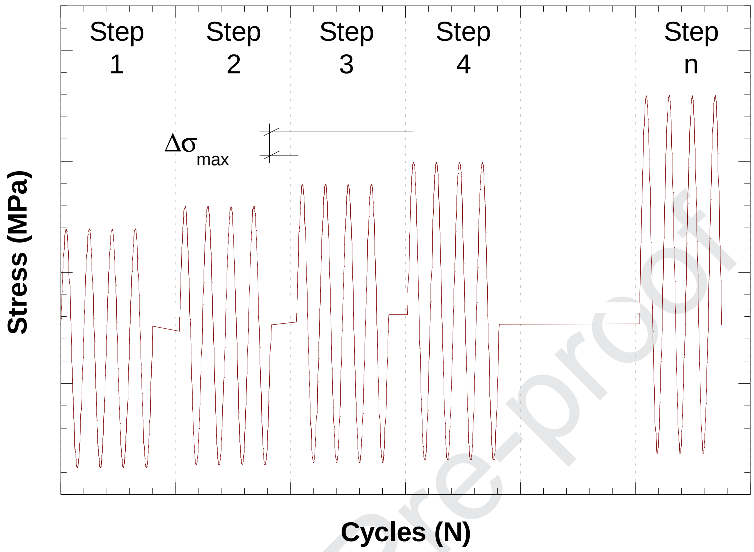


Fig. 3: *Locati test example where five different steps can be seen. The first four consecutively and the fifth corresponding to a step "n".*

Table 6: *Mechanical properties.*

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

The evolution on the compressive strength shows the great influence of w/c ratio on compressive strength, which is the reason why the compressive strength of RC-S is higher than that of RC-B in spite of having poorer quality aggregates. Furthermore, the effect of the fly ash contained in CEM type IV is noticeable, as it causes the resistance to increase notably after 28 days. It can also be seen that the strength of RC-M is in all cases between those of RC-B and RC-S (Sainz-Aja, 2019).

In the case of the Young's modulus, due to the higher stiffness of the crushed ballast aggregates, the corresponding concrete's stiffness is also higher, although the mortar quality of RC-B is lower than that of RC-S because of the difference in the w/c ratio.

3.2. Staircase test results

First, the Staircase tests were used to obtain the fatigue limit by means of the standardized Staircase procedure, the results of which are shown in Table 7.

Table 7: *Fatigue limit according to the Staircase tests.*

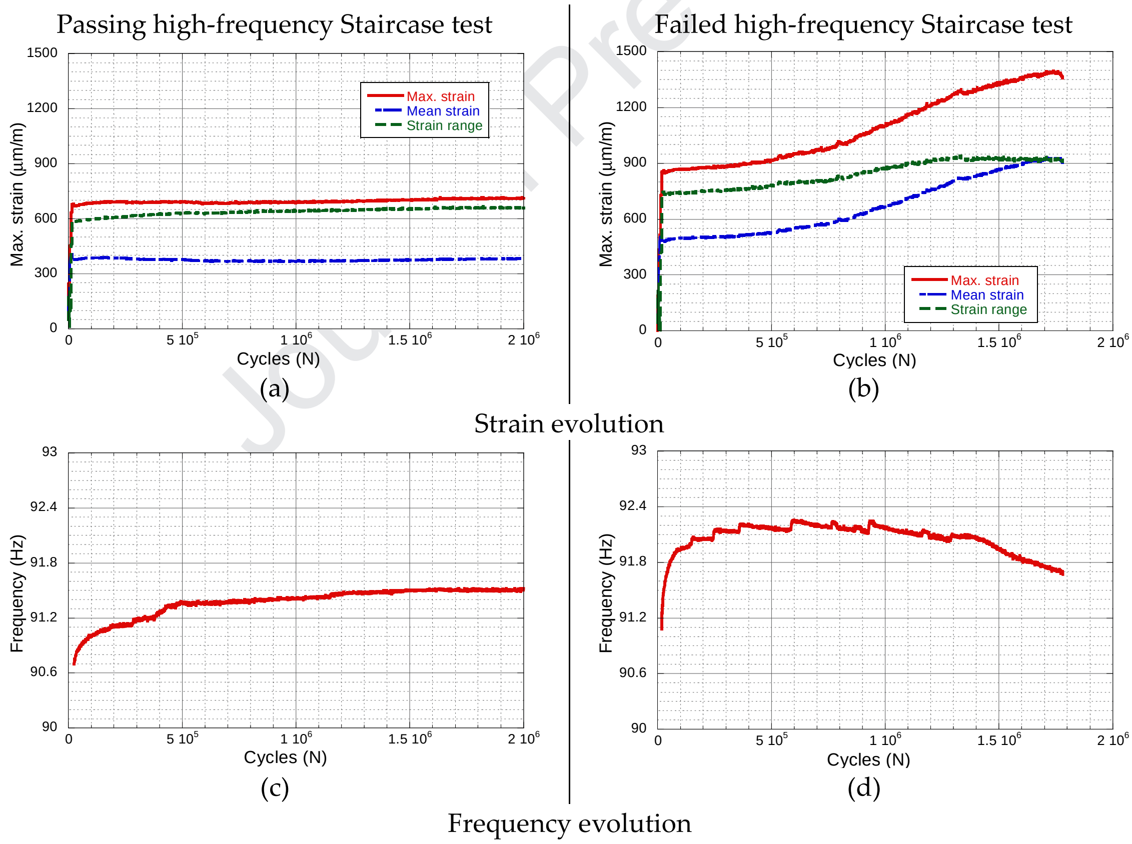
Material	$\Delta\sigma_{FL}$ (MPa)	$\Delta\sigma_{FL'}$ (%)
RC-B	28.1±2.7	47.4±4.5

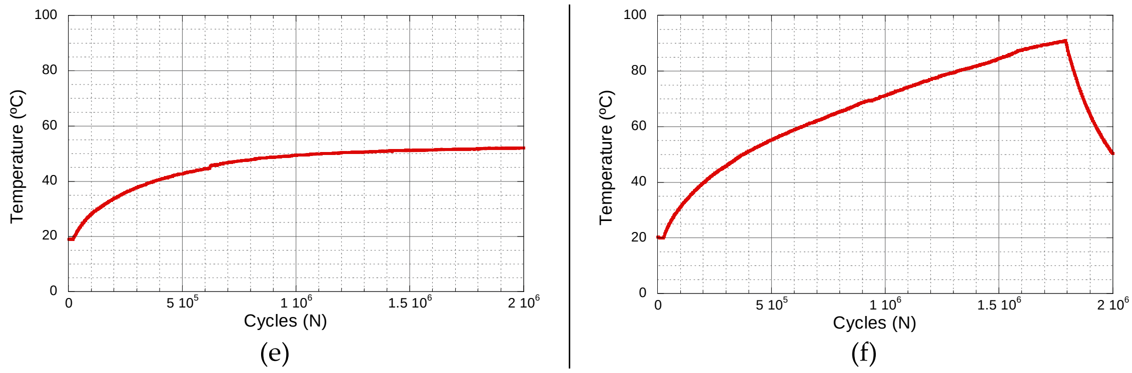
RC-S	28.0±3.5	36.1±4.5
RC-M	27.8±2.8	44.1±4.5

The fatigue limits of the three concrete mixes are similar. If the ratio fatigue limit/compressive strength is analysed, a reduction can be seen in RC-S caused by the presence of recycled concrete aggregates. This reduction in this ratio has been previously detected by other authors (Sainz-Aja et al., 2019c; Thomas et al., 2014).

To understand as well as possible the phenomenon that produces fatigue failure in concrete, the values of strain, resonance frequency and temperature were registered throughout the test. Fig. 4 (a), (c) and (e) show a test case where a specimen successfully passes the Staircase test step, while Fig. 4 (b), (d) and (f) show a test case where the specimen does not pass the step.

Regarding concrete strain evolution, when the specimen passes, a stabilization of the maximum, mean and strain range is observed after a few cycles. When the specimen does not pass, strain starts to grow increasingly faster until it breaks, which is consistent with previous observations (Li et al., 2016; Sainz-Aja et al., 2019c). Regarding the resonance frequency evolution, when the specimen passes, the resonance frequency stabilizes, while when the specimen does not pass, the frequency increases in a first phase, after which it is more or less stable until the final stage, when it starts to decrease before breaking, which is also consistent with previous observations (Sainz-Aja et al., 2019c).





Temperature evolution

Fig. 4: Comparison of a passing with a failed high frequency Staircase test (RC-M). The same phenomenon has been represented in three different ways. Firstly, evolution of strain, secondly frequency and finally temperature, all of them against the number of fatigue cycles.

Regarding the temperature evolution of the external surface of the specimen, when the specimen passes, similarly to the deformation and frequency, temperature will stabilize, at 60 ± 5 ºC in all cases. When the specimen does not pass, in contrast to what happens with frequency or deformation, two types of behaviour occur depending on whether the test specimen breaks within the first phase of the step or, on the contrary, it withstands most of it. It has been found that in the first case, the increase in temperature can be significantly variable, while if it withstands enough cycles, the temperature values of the external face of the specimen rise to approximately 100 ºC. This phenomenon is observed for the three concrete mixes. This increase in specimen temperature may be due to fatigue friction between the contacting faces of the fissures, generating energy.

The difference between low and high frequency is that in high-frequency tests the time between cycles is not sufficient to dissipate the heat generated by that friction, so the energy is accumulated in the specimen, continuously increasing the temperature until failure. When the friction stops, the temperature begins to fall. For specimens that break after a few cycles, they accumulate this energy for a short time, so its temperature may not increase as much as when they withstand more cycles.

In addition, focusing on the failing tests, the evolution of both temperature and test frequency as a function of strain can be seen in Fig. 5 and Fig. 6.

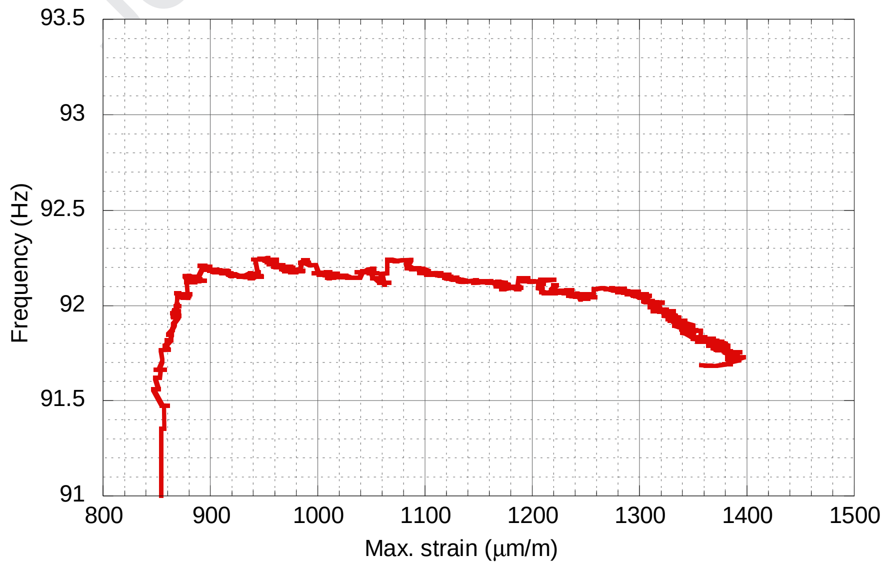


***Fig. 5:** Evolution of resonance frequency as a function of max. strain during high-frequency fatigue failure (RC-M). Result of the variation by automatic adjustment of the resonance frequency during the Staircase test, allowing observing the initial increase and the decrease with the loss of stiffness of the material.*

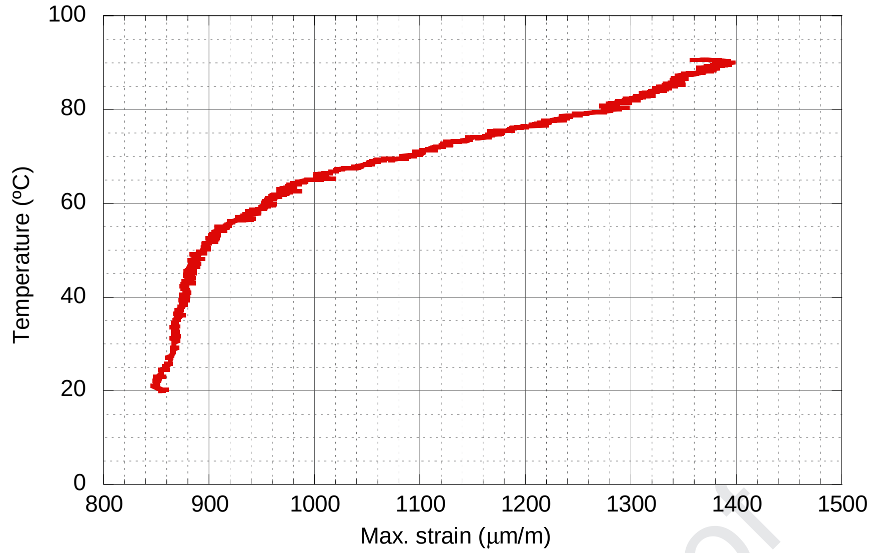


Fig. 6: *Evolution of temperature as a function of max. strain during high-frequency fatigue failure (RC-M). A continuous increase of temperature by accumulation of energy due to fatigue cycles is observed.*

Fig. 5 and Fig. 6 show that there is a first stage, when strain reaches approximately 900 µm/m. For resonance frequency, up to that point it increases with the increase in strain, while from that point on it starts to fall. For temperature, up to 900 µm/m its growth is much faster than from that point on. In addition, it can also be observed that, at the point that marks this change in trend, the external face is above 60 ºC. When the temperature exceeds that range of temperature, the test specimen is close to breaking.

3.3. Locati test results

To be able to compare the Locati method with the Staircase method, it is necessary to check that the number of Locati cycles applied per step is suitable. For this purpose, Locati tests were carried out applying 2×10^5 and 5×10^5 cycles per step and the results of L2 and L5 were compared and similar results were obtained. Fig. 7 shows the maximum strain of an example of each binomial material & number of cycles per step. Fatigue limit results, according to the two methods described in materials and methods, are presented in Table 8.

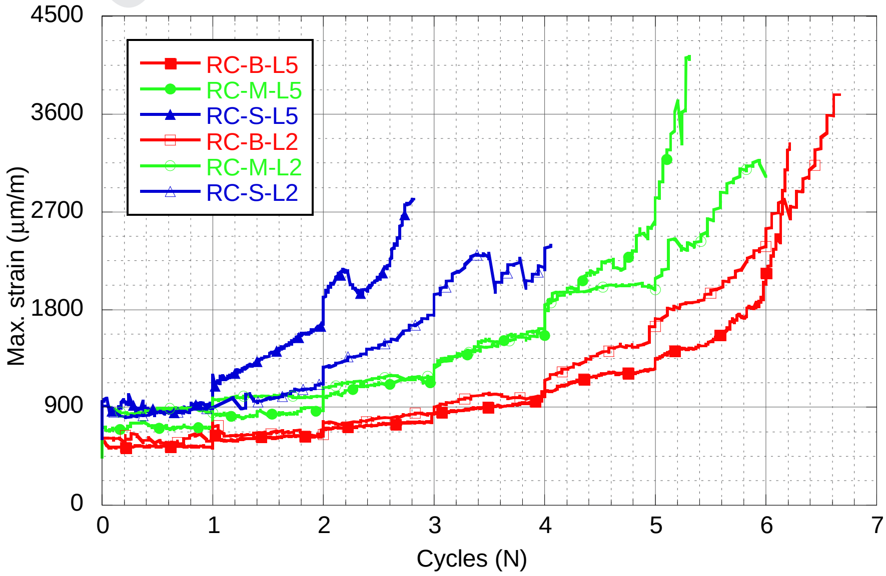


Fig. 7: *Example of maximum strain for each binomial material & number of cycles per Locati step. Its evolution is represented by different colours: red for RC-B, green for RC-M and blue for RC-S.*

Table 8: *Fatigue limit according to Locati tests.*

Material	Method-1		Method-2	
	ΔσFL (MPa)	ΔσFL′ (%)	ΔσFL (MPa)	ΔσFL′ (%)
RC-B-L5	24.6±2.7	43.2±4.5	26.7±2.7	45.1±4.5
RC-S-L5	23.8±3.5	30.7±4.5	24.5±3.5	31.5±4.5
RC-M-L5	23.7±2.8	37.7±4.5	25.5±2.8	40.5±4.5
RC-B-L2	25.7±2.7	45.1±4.5	26.7±2.7	46.9±4.5
RC-S-L2	25.2±3.5	32.4±4.5	28.0±3.5	36.1±4.5
RC-M-L2	24.9±2.8	39.5±4.5	28.3±2.8	44.9±4.5

Comparing the fatigue limit results and maximum strain values of the two types of Locati tests, the L2 results are more conservative than those of L5, but that the difference between them, in the worst case, is one Locati step. So, due to the inherent dispersion of both concrete and fatigue, it can be considered that the methods provide similar results.

3.4. Correlation of methods

In this section, the fatigue limit values for all methods, are compared. Fig. 8 shows the five fatigue limits obtained by those different methods on the left, while, on the right, the five values of fatigue limit/compressive strength are compared.

In all cases method-1 is more conservative than method-2. If the results L2 and L5 are compared, in all cases L5 is more conservative. Finally, in all cases the Locati method is more conservative than the Staircase method.

Using the Staircase method as reference given that it is the standardized and most used method, it is possible to state that the Locati method gives in all cases more conservative, but quite similar results, and those analysed through L-2/M-2 provide the closest results to those obtained by the Staircase method.

In Fig. 9, the fatigue limit value obtained by the Staircase method is shown in the x axis while the value determined by the Locati methods is shown in the *y* axis.

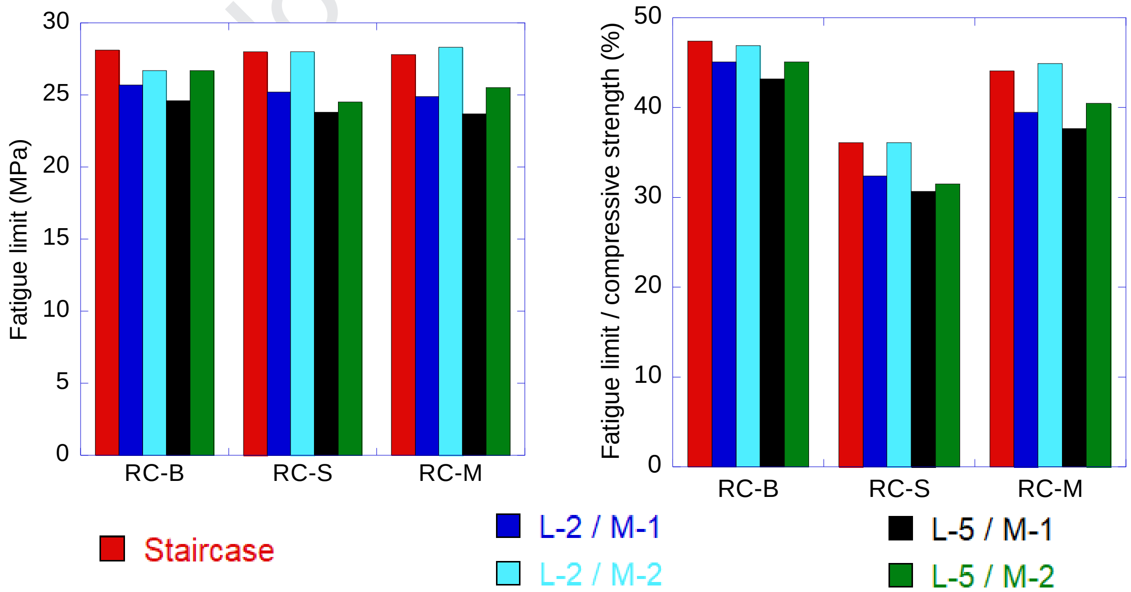


Fig. 8: *Comparison of the high-frequency fatigue limit and of the low-frequency fatigue limit, obtained through five alternative procedures. The control test is shown in red and those proposed in this research are shown in blue, black and green.*

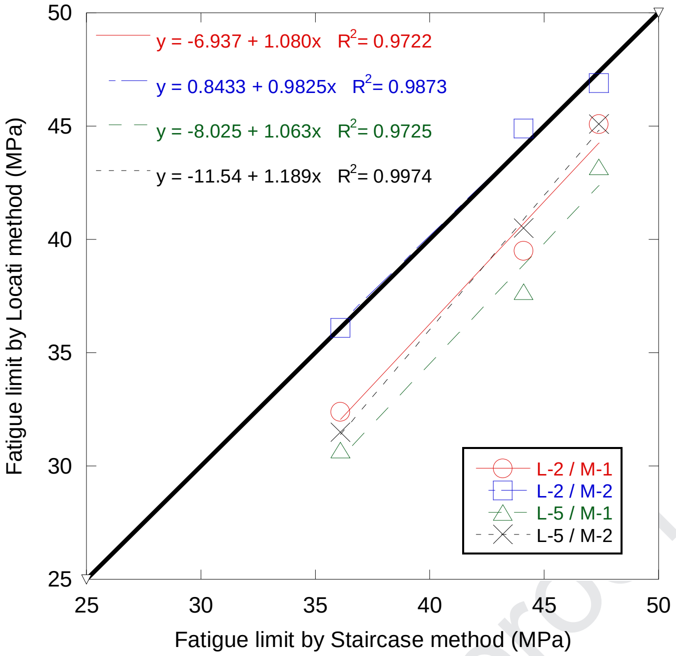


Fig. 9: *Correlation Staircase vs. Locati method. All the adjustment lines are below the 45-degree line, the furthest being the green one corresponding to the L-5 / M1 case.*

From Fig. 9, it can be concluded the results provided by the Locati method and the Staircase method are proportional. Note that the slope of all the regression lines, except for L-5/M-2, is 1 ± 0.08. Also, the parameters used to define the Locati test, number of cycles per step, and analysis procedure, have some influence on the correlation between the fatigue limit obtained by both methods. For L-2/M-2, the results are practically the same in both methods, and L-2/- 1, L-5/M-1 and L-5/M-2 are more conservative. It can also be concluded that method 1 is more conservative than method 2 and applying 2×10^5 cycles per step is more conservative than applying 5×10^5 cycles per step.

4. Costs-related remarks

A reduction in the number of tests will have a consequent economic cost reduction in the fatigue characterization of the recycled concrete. In general, fatigue characterization tests are budgeted according to the machine hours required to perform the tests. As the testing time is directly related to the testing frequency, in this point it will be only compare the effect of using the Locati method instead of the Staircase method, without analyzing the effect of the frequency.

The characterization time for Locati tests will be approximately 7 steps of 2×10^5 cycles, performing two tests per material. In the case of characterization by the Staircase method, there will be a total of at least 9 tests, of which approximately 50% will reach 2×10^6 cycles and, let us assume that the other 50% will remain at 1×10^6 cycles. Under these assumptions, the characterization by the Staircase method is almost 5 times higher than by the Locati method.

5. Conclusions

The importance of designing concrete elements bearing fatigue in mind is becoming increasingly clear. For this reason, it is essential to identify a method that allows determining concrete fatigue limit as fast, economically and accurately as possible. In order to achieve this objective, two test methods have been compared in this work, the standardised Staircase method and a method that proposes determining fatigue limit from a single test specimen, the Locati method. In addition, the number of cycles per step, in the Locati method, was analysed through testing. These fatigue tests were performed on three self-compacting recycled concrete types. The first one used recycled aggregate from crushed ballast, which has a similar behaviour to natural aggregate. The second one used recycled aggregate from crushed concrete sleepers. Finally, a third concrete had 6/7 of aggregate from crushed ballast and 1/7 of aggregate from crushed sleepers. In order to reduce the duration and, consequently, the cost of the fatigue tests as much as possible, these tests were carried out in a resonance machine at a frequency of approximately 90 Hz. The following conclusions can be drawn:

- The results provided by both methods, Staircase and Locati, are comparable, and the Locati method is more conservative;
- Applying 2×10^5 or 5×10^5 cycles per step does not significantly change the fatigue limit provided by the Locati method. For 2×10^5 cycles per step, the results are closer to those provided by the Staircase method, while being more conservative;
- The analysis of the Locati tests by method-1 (80% of the stress range in the breaking step) or method-2 (stress range in the previous step of a resonance frequency drop) provides similar results. In all cases results closer to those provided by the Staircase method were obtained using method-2. However, all cases were conservative;
- The Locati Method is particularly suitable for those cases in which concrete samples are taken from an existing structure, since it requires extracting less samples;
- It is concluded that the Locati method is capable of determining the fatigue limit of concrete similarly to the Staircase method, with the great advantage of significantly reducing the number of specimens needed. For this reason, it is concluded that the optimum method to determine the fatigue limit is the Locati Method with 2×10^5 cycles per step, since it provides similar results to the others with a lower number of tests, lower test duration and, consequently, cheaper procedures.

For the valorisation of construction and demolition waste as recycled aggregates in the manufacture of recycled aggregate concrete, it is necessary to have a wide knowledge about RC behaviour. In this paper a step has been taken in that direction, optimizing the procedure to determine the fatigue limit of these concrete mixes.

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Fast fatigue method for self-compacting recycled aggregate concrete characterization

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: