Long-term flexural performance of reinforced concrete beams with recycled coarse aggregates

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Abstract

The aim of this study is to investigate the behaviour of recycled aggregate concrete subjected to sustained loading. For the tests, eight reinforced concrete beams were manufactured with recycled coarse aggregate, using water-to-cement ratios of 0.50 and 0.65, and four replacement percentages: 0%, 20%, 50%, and 100%. First, the basic concrete properties, mechanical strength and modulus of elasticity, were determined after 28 d, and at the ageing load. The beam specimens were then loaded at 42 d, using a four-point bending test. Bending moments and deformations were obtained during the loading process, when cracking and serviceability conditions were reached, as well as the long-term deformations of recycled concrete beams up to 1000 d.

Based on these results, it can be reported that long-term deformations are greater for recycled aggregate concrete than for conventional concrete, regarding both strain and deflection. Furthermore, a direct relationship was found between these deformations and the replacement percentage used. Lastly, code-based expressions were used to calculate the long-term deflections of RC beams subjected to sustained loading, which included the recycled coarse aggregate content and corrections previously proposed to predict the mechanical properties, creep, and shrinkage of recycled aggregate concrete.

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Key words: recycled aggregate concrete; flexural performance; long-term deflection; long-term strain; sustained load.

Nomenclature

t	Concrete age (days, d)
t_o	Loading age (days, d)
$t-t_o$	Time under sustained load (days, d)
σ	Compressive stress (MPa)
σ/f_c	Stress level (%)
f_c	Compressive strength by cylinder specimens of 15 × 30 cm at 28 d
$f_{c,42}$	Cylinder compressive strength at 42 days, (specimens of 15 × 30 cm)
E_c	Modulus of elasticity at 28 d
$E_{c,42}$	Modulus of elasticity at 42 d
ε_{sh} (42, 1042)	Shrinkage strain at 1000 d after loading
φ (42, 1042)	Creep coefficient at 1000 d after loading
M	Bending moment at beam´s midspan (kN·m)
M_{cr}	Cracking moment at beam´s midspan (kN·m)
M_Q	Acting moment at beam´s midspan (kN·m)
δ_{cr}	Cracking deflection at beam´s midspan (mm)
δ_o	Immediate deflection at beam´s midspan at 42 d (mm)
δ ($t-t_0$=1000 days)	Total deflection at beam´s midspan at 1000 d after loading (mm)
δ_{dif} ($t-t_0$=1000 days)	Long-term deflection at beam´s midspan at 1000 d after loading (mm)
δ_{sh}	Shrinkage deflection at beam´s midspan (mm)
δ_{φ}	Creep deflection at beam´s midspan (mm)
k_{sh}	Shrinkage induced curvature
ε_0	Elastic strain of concrete at t_0
ε ($t-t_0$=1000 days)	Total concrete strain at beam´s midspan at 1000 d after loading
ε_{dif} ($t-t_0$=1000 days)	Long-term concrete strain at beam´s midspan at 1000 d after loading

1 INTRODUCTION

The use of recycled aggregate for structural concrete has been widely recognised as a means of reducing the issues associated with concrete waste. In order to promote environmentally friendly practices and procedures in the construction field, numerous attempts have been made to provide useful guidelines, and to encourage the use of more sustainable concrete structures, which include recycled aggregate from concrete demolition debris. In this regard, broad experimental programmes have been conducted by numerous researchers to assess recycled concrete behaviour with different replacement percentages.

It is generally accepted that the use of recycled aggregate influences basic concrete properties, such as density, mechanical strength, and modulus of elasticity [1–19], as well as long-term properties, such as creep and shrinkage strain [20–25]. However, the study of the structural performance of recycled concrete is not yet widespread, and although numerous researchers have studied structural recycled concrete, only a limited number of the studies actually included full-scale structural tests. The bulk of these structural studies focused on bond behaviour [26–29], or short-term RC beam behaviour [30–39].

In order to contribute to a better understanding of, and greater confidence in, the use of recycled concrete, recent studies [40,41] have analysed Eurocode predictions to design structural recycled concrete, based on the results of other researchers. One such study [40] carries out a parametric analysis of structural concrete, while incorporating recycled aggregates according to Eurocode 2. Therefore, we propose an equivalent functional unit that enables us to predict structural behaviour, by considering the different mechanical and durability performances of recycled concrete. Another study [41] assesses the accuracy and precision of Eurocode 2, when calculating the flexural strength of structural recycled concrete members using a database. However, these studies are focussed on the short-term behaviour of recycled concrete beams, including flexural strength and analysis at failure, and do not provide experimental results.

Regarding the long-term structural behaviour of recycled concrete, experimental results available for establishing good agreement on its full load-deformation response are scarce.

2 RESEARCH SIGNIFICANCE AND OBJECTIVES

Few researchers have conducted experimental studies on RC beam flexural behaviour when subjected to sustained loads [42,43].

Knaack and Kurama [42] report that an increase in recycled aggregate content results in a reduction in initial stiffness, and an increase in deflections. They conclude that code-based procedures, according to the Eurocode and the American Concrete Institute (ACI), used with conventional concrete can also be applied to predict recycled concrete flexural behaviour. Furthermore, they suggest that additional studies should be conducted to further investigate the use of recycled aggregates in reinforced concrete, e.g. long-term creep and shrinkage deformations, age effects and strength gain of concrete, prediction of concrete properties, and service-load and ultimate-load behaviour.

Other studies on the long-term deflections of recycled concrete [43] reported that recycled concrete beams exhibit a similar crack pattern to conventional ones. In terms of deflections, the long-term to instant deflection ratios of recycled concrete beams are lower than those of conventional beams. However, both recycled and conventional concrete beams satisfy the maximum permissible deflections according to the ACI code provisions. The long-term deflections can also be calculated according to the modified ACI approach, providing acceptable agreement with the experimental results. Lastly, because of the reduction of interfacial bonding strength between the mortar and recycled coarse aggregate, differences in the neutral axis depth of the beam have been detected with 100% recycled aggregate.

These studies [42,43] deal with time-dependent deformations up to 140 d and 380 d after loading, respectively. However, the results obtained indicated that the time-dependent deformations had not yet stabilised, and concrete deformations tended to increase over time. Therefore, further analysis of this issue is required, in order to determine the long-term behaviour of recycled concrete after one year.

Based on a literature review, it can be concluded that further research is required to evaluate the effect of recycled coarse aggregate content on the long-term performance of structural concrete. Therefore, this work deals with the analysis of the flexural performance of recycled concrete subjected to sustained load over time (after one year), in order to provide trustworthy guidelines for it to be designed with the same structural reliability as conventional concrete.

3 EXPERIMENTAL PROGRAM

This study is part of an extended research project to further analyse the flexural performance of structural recycled concrete. Physical and mechanical properties, bond behaviour, shrinkage, and creep have already been evaluated in previous studies [28,44–46]. In terms of flexural behaviour, short- and long-term analyses have been conducted. For this test, two series of eight reinforced concrete beams were manufactured with different recycled aggregate replacement percentages. One of these series was loaded up to failure at 28 d in order to analyse the short-term behaviour of RC beams. The other eight twin RC beams were subjected to sustained load for 1000 d, in order to evaluate the long-term performance of recycled aggregate concrete.

This study focusses on this last analysis. The long-term behaviour of RC beams manufactured with recycled aggregate tested in flexure, and basic concrete characterisation, both in fresh and hardened states, was also covered.

3.1 Materials and concretes used

CEM I– 52.5N/SR cement, according to EN 197-1, and a superplasticiser, SIKAMENT 500 HE, as a water reducing admixture, were used. Three different coarse aggregate size fractions were used, including two natural aggregates from crushed limestone, and one recycled aggregate obtained from the demolition of concrete structures, primarily comprising aggregate with adhered mortar. In the case of the fine aggregate, only natural sand was used, which was also obtained from crushed limestone. Table 1 summarises the basic properties of these aggregates, and Fig. 1 shows their grading curves.

Table 1 Basic properties of aggregates used [28,44–46].

		0-4N	***8-20N***	***4-12N***	***4-16R***
Density (EN 1097-6)	kg/m^3	2669.4	2655.9	2610.4	2566.0
Density in oven-dry conditions (EN 1097-6)	kg/m^3	2520.3	2565.2	2468.8	2254.0
Water Absorption (EN 1097-6)	%	2.2	1.3	2.2	5.4
Los Angeles Abrasion (EN 1097-2)	%	--	23.1	--	34.3
Fineness module (EN 933-1)		3.7	7.4	6.2	7.2
Fines percentage (EN 933-1)	%	11.5	0.4	1.5	0.3
Moisture content (EN 933-1)	%	0.1	0.1	0.1	2.9

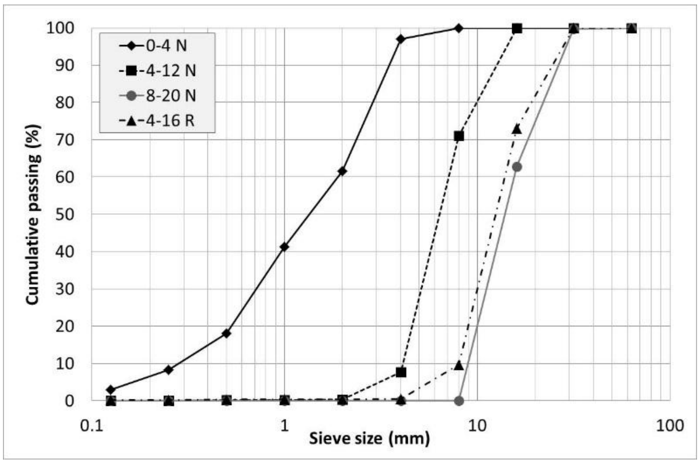


Fig. 1 Aggregate grading curves

Two concrete series were designed using this material, with water to cement ratios of 0.50 and 0.65, designated H50 and H65, respectively. Each series comprised four concrete types, three of which were made with different replacement percentages, conventional coarse aggregate replaced with recycled aggregate, and one with 0% replacement to provide the baseline concrete. Eight different concretes were then designed, designated as H50-0, H50-20, H50-50, H50-100, H65-0, H65-20, H65-50, and H65-100.

It is widely known that recycled aggregates exhibit a high water absorption capacity because of adhered mortar [44,47,48]. This reduces the water available in the concrete mix, which influences the concrete properties, and leads to a specific mixing process being required. In this study, recycled aggregates were pre-saturated up to 80% of their water absorption, before mixing.

This pre-saturation process comprised pre-soaking the recycled aggregate for 10 min, and then draining it for a further 10 min. When this process was complete, the aggregates were weighed. If their weight indicated that the degree of saturation was 80% ± 5%, then the pre-saturation stage was complete. Deviations from of this process were measured, and the effective water to cement ratio of each concrete was calculated. Table 2 presents the concrete proportions for 1 m^3.

In order to characterise the concrete samples, their basic properties were determined. First, the fresh concrete properties were obtained by measuring their consistencies using the slump-test (EN 12350-2), and densities in accordance with standard EN 12350-6. Two cylindrical specimens of 10 × 20 cm were used to determine the density and water absorption of each concrete at 28 d, in accordance with EN 12390-7. As already reported by other authors [47,49], the water absorption coefficient increases, and density decreases, in both the fresh and hardened states, as the replacement percentage increases, because of the adhered mortar of the recycled coarse aggregate [47,48,50].

Table 2 Mix proportions for 1 m^3.

		Concrete H65				**Concrete H50**			
		0%	**20%**	**50%**	**100%**	**0%**	**20%**	**50%**	**100%**
Cement	kg	275.00	275.00	275.00	275.00	380.00	380.00	380.00	380.00
Water	kg	178.75	178.75	178.75	178.75	190.00	190.00	190.00	190.00
0-4N	kg	918.49	938.05	962.73	1005.18	781.43	794.31	811.37	838.29
8-20N	kg	486.19	372.47	218.29	0.00	665.44	512.76	303.34	0.00
4-12N	kg	457.65	350.60	205.48	0.00	307.93	237.28	140.37	0.00
4-16R	kg	0.00	180.77	423.77	756.46	0.00	187.51	443.71	807.97
w/c		0.65	0.65	0.65	0.65	0.50	0.50	0.50	0.50
Effective w/c		0.65	0.66	0.67	0.68	0.50	0.51	0.51	0.52
Admixture	%	0.85	1.20	1.07	1.00	1.03	1.17	1.20	0.87

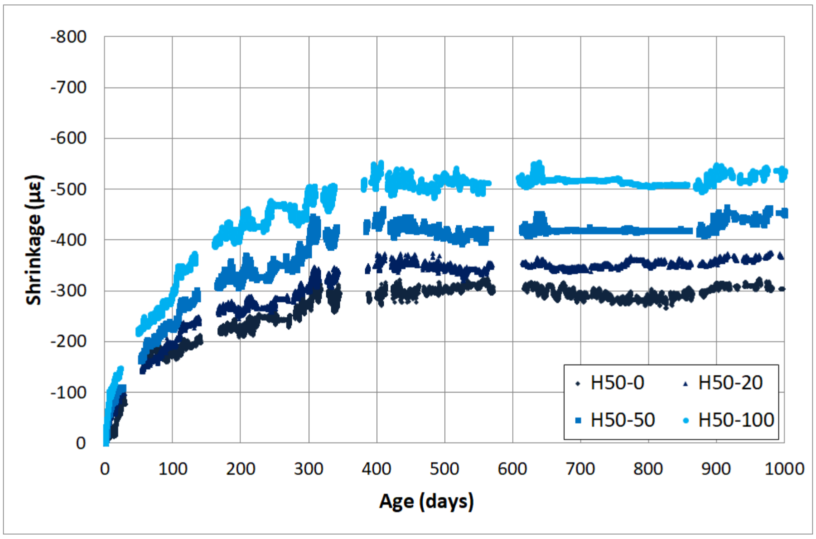
The mechanical properties were also determined. Three cylindrical specimens, of 15 × 30 cm, were used to obtain the compressive strength and modulus of elasticity in accordance with EN 12390-3 and EN 83316, respectively. These mechanical properties were evaluated at 28 d and 42 d, which are the age of the flexural test by load to failure, and the loading age of the long-term test under sustained load, respectively. As expected, the compressive strength and modulus of elasticity of recycled concrete decreased as the replacement percentage increased.

To further analyse the long-term performance of recycled concrete, time-dependent strains from creep and shrinkage, which are comprehensively discussed in a previous study, were also obtained, [46]. Shrinkage was measured using two prismatic specimens (15 × 15 × 60 cm), with a strain gauge embedded at the centre of these specimens. The strain gauge was continuously monitored for 1042 d, using a data acquisition system. Creep strains and creep coefficients were calculated using the experimental deformations measured on two cylindrical specimens, subjected to sustained load over 1000 d, which were tested simultaneously with the RC beams. In this manner, creep strains, and consequently creep coefficients, were obtained as the total strain measured over time, less the instantaneous strain at loading age and shrinkage induced strain [46]. Table 3, Fig. 2 and Fig 3 summarise these concrete properties, which were presented in previous studies [28,46].

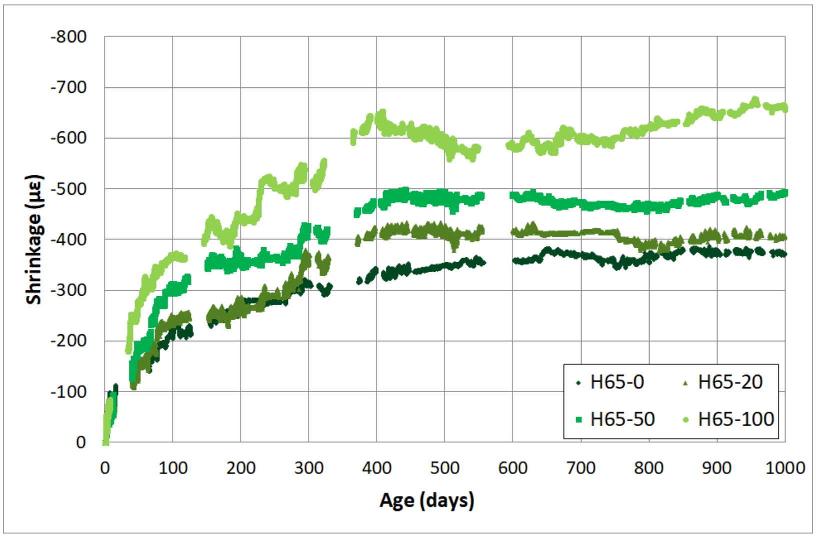
Table 3 Concrete properties

Concretes H65		**0%**	**20%**	**50%**	**100%**
Slump values	cm	6	10	12	16
Density of fresh concrete	t/m^3	2.37	2.35	2.32	2.28
Density of hardened concrete	t/m^3	2.31	2.26	2.26	2.22
Absorption of concrete	%	2.63	2.95	2.83	3.77
f_c	MPa	46.9	46.7	42.2	32.4
$f_{c,42}$	MPa	50.3	47.2	41.6	32.3
E_c	MPa	35152.4	32531.9	27410.7	24053.9
$E_{c,42}$	MPa	36552.5	34312.0	29300.7	23982.4
$\varphi_{(42,1042)}$		1.22	1.36	1.49	1.75
ε_{sh} (1042)	$\mu\varepsilon$	-371	-406	-493	-656
Concretes H50		**0%**	**20%**	**50%**	**100%**
Slump values	cm	16	17	16	19
Density of fresh concrete	t/m^3	2.38	2.36	2.34	2.29
Density of hardened concrete	t/m^3	2.32	2.30	2.28	2.23
Absorption of concrete	%	1.38	1.81	1.75	2.60
f_c	MPa	60.7	53.5	51.8	42.9
$f_{c,42}$	MPa	65.7	59.1	53.1	45.3
E_c	MPa	36297.4	32874.9	31550.0	25862.3
$E_{c,42}$	MPa	38532.7	35301.0	31766.1	26851.9

$\varphi_{(42,1042)}$		1.15	1.15	1.11	1.47
ε_{sh} (42, 1042)	με	-304	-366	-448	-537

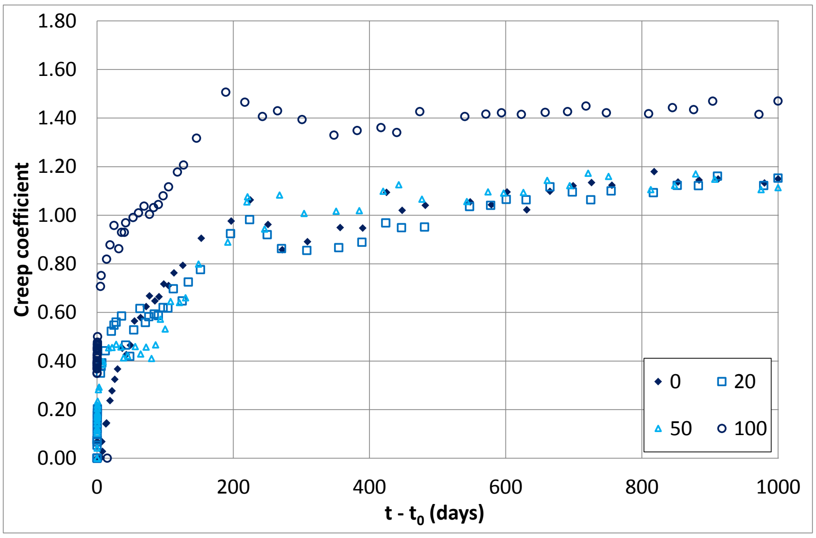


a) H50 series RC beams

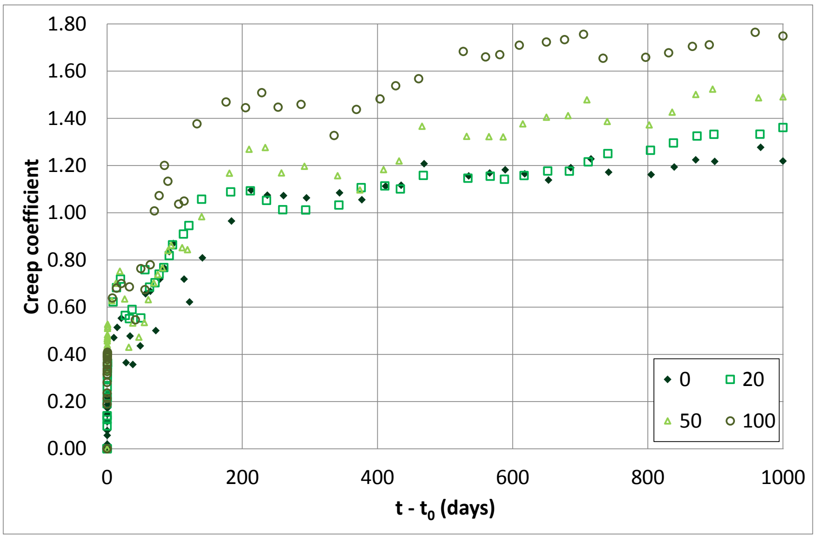


b) H65 concretes

Fig. 2 Shrinkage over time [46]



a) H50 concretes



b) H65 concretes

Fig. 3 Creep coefficients [46]

All concrete specimens were cured with soaked burlap for 48 h after casting. They were then stored in the laboratory, up to the testing age, in order to be exposed to the same environmental conditions as those of the RC beams.

The reinforcing bars were of B500SD steel, with an elastic modulus of 210 000 MPa, and a yielding strength of 516.93 MPa (>500 MPa).

3.2 Concrete beams

The RC beams were designed to analyse the flexural behaviour of RC containing recycled aggregate, subjected to a sustained load for 1000 d. All beams had a rectangular cross section of 30 × 20 cm (height × width), were 360 cm long, and with a single span of 340 cm, as shown in Fig.

4. They were designed according to structural codes, while [51,52] taking typical service conditions into consideration. The reinforcement was designed to obtain a ductile mode of failure.

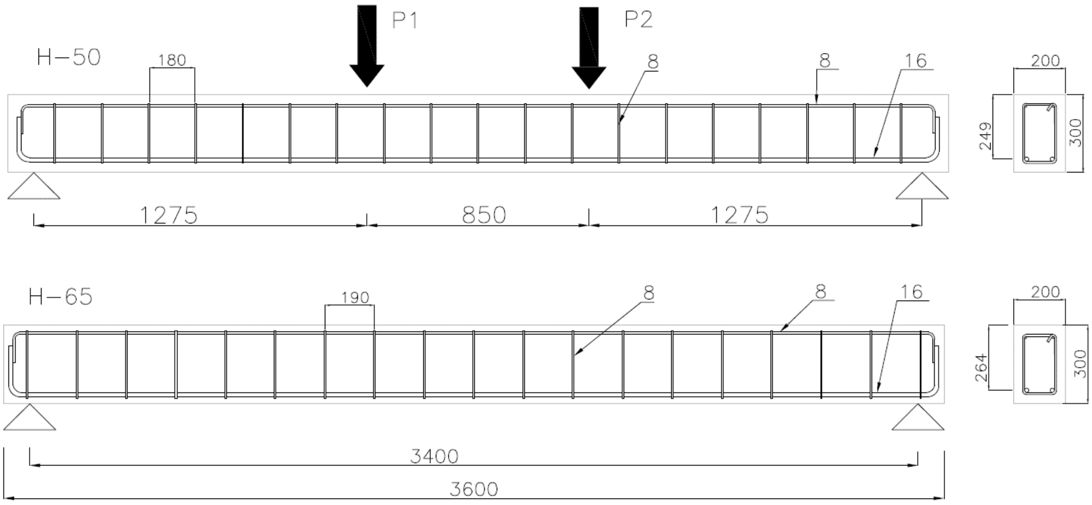


Fig. 4 Beam specimens (mm)

The longitudinal tensile reinforcement ratios were 0.81% and 0.76% for the H65 and H50 beams, respectively. Although the compression steel was not required according to the code-based structural design, a minimum amount was included for better stirrup distribution in the RC beams.

The stirrups were 8 mm-steel rebars, placed at 180 mm intervals for H50 series RC beams, and 190 mm intervals for the H65 series RC beams. The interval difference was because of the different concrete covers of each RC beam series.

3.3 Tests under sustained load

Long-term tests were conducted on RC beams, supported at two points and under a sustained load, for 1000 d. A four-point bending test system, as shown in Fig. 5, was used. In this manner, a constant bending moment was generated in the central span of the beam, where the maximum deflections, strains, and moments are produced.

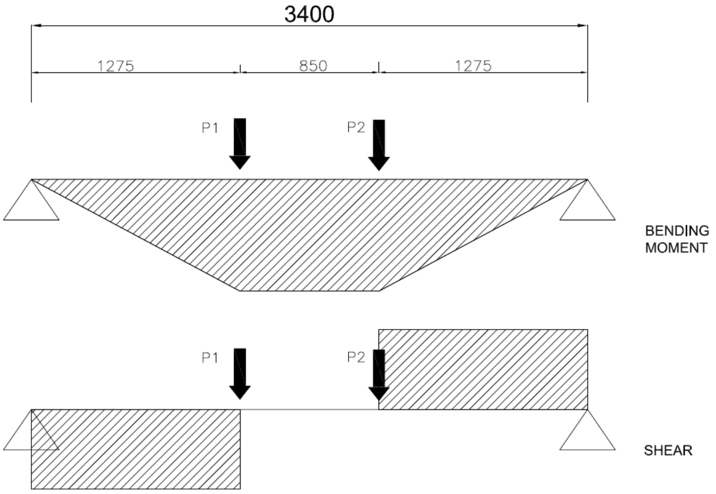


Fig. 5 Bending moment and shear distribution of RC beams from loading procedure (mm)

The sustained load was applied at 42 d. This involved a lever system, in which the load was applied by means of a metal frame resting on the beam, from which a dead weight was hung at one end, while the other end was fixed to the load slab in the laboratory by a tensed tie rod. Using a pulley system, the tie rod was used to generate a compression force on two of the cylindrical specimens located at the core of a creep frame, located under the load slab on which it was supported. This test system, shown in Fig. 6, produces similar strain, both in the cylindrical specimens and in the fibre most compressed in the beam central section, in such a manner that the beam and specimen tests can be conducted simultaneously.

The test load was calculated with the aim of generating strain in the concrete within its elastic range, both in the beams and specimens. Therefore, the strain value was set for the concrete at 30% of its maximum compression strength at 42 d (load age). In this manner, all concretes were tested under service conditions.

Steel and concrete strain gauges were used to measure the strain in the central section of the beams, two load cells were used to control the load levels in the beams and specimens, and displacement transducers (Fig. 7) were used in the central section of the beams to record the deflections produced in each concrete studied during the test. From the recorded data, the actual load and strain values of the concrete were determined (Table 4), which showed that the beam and specimen tests were conducted inside the elastic range of the concrete.

Fig. 8 shows the environmental conditions of temperature and humidity in the laboratory. Both parameters were continuously recorded during the test ($t-t_0$ = 1000 d), and an average temperature of 15 ºC and average humidity of 75% were obtained.

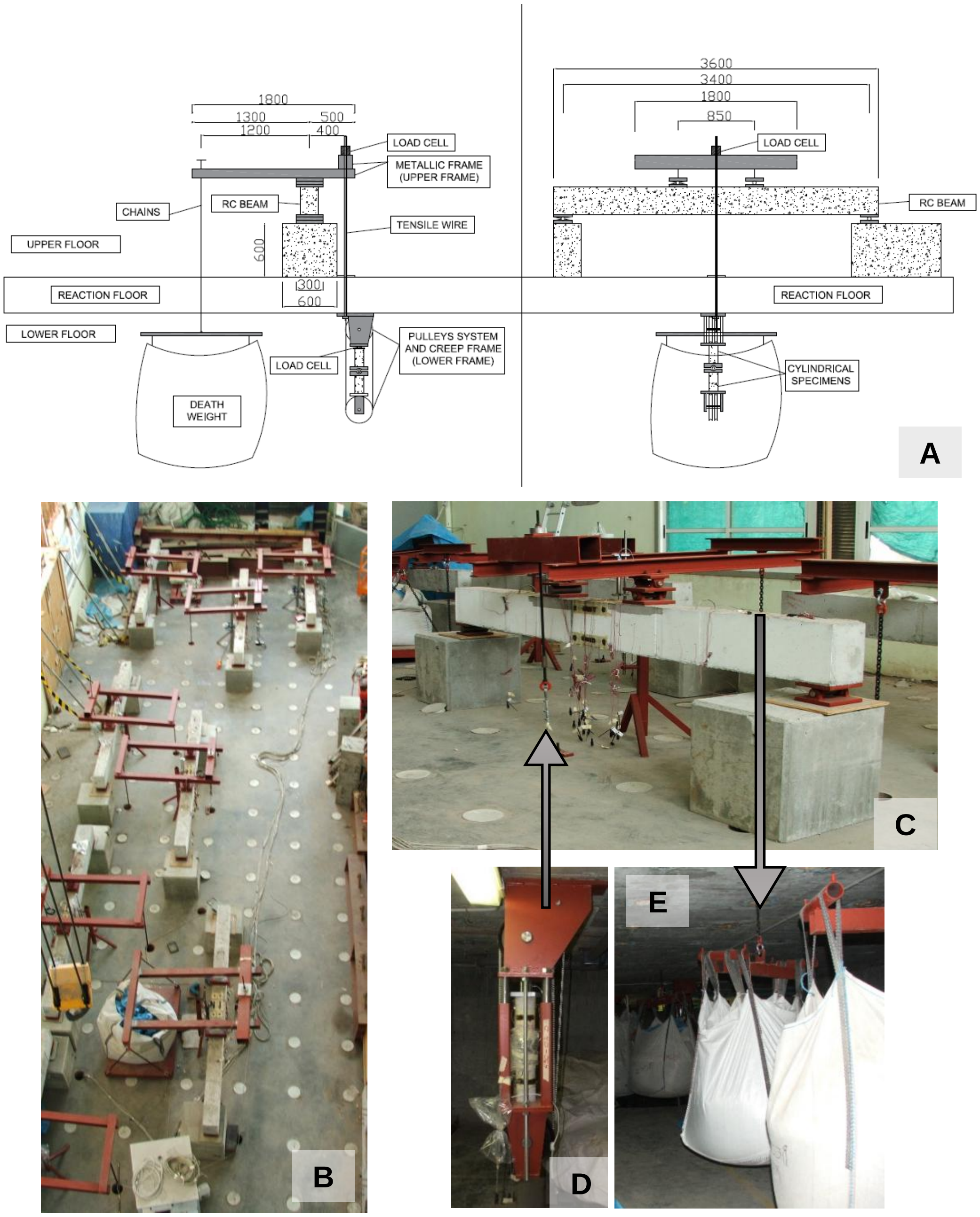


Fig. 6 Test set-up. A: Test equipment B: RC beam layout for tests under sustained load. C: RC beam subjected to a sustained load. D: Concrete cylinders at creep frame. E: Dead load on metal load frame

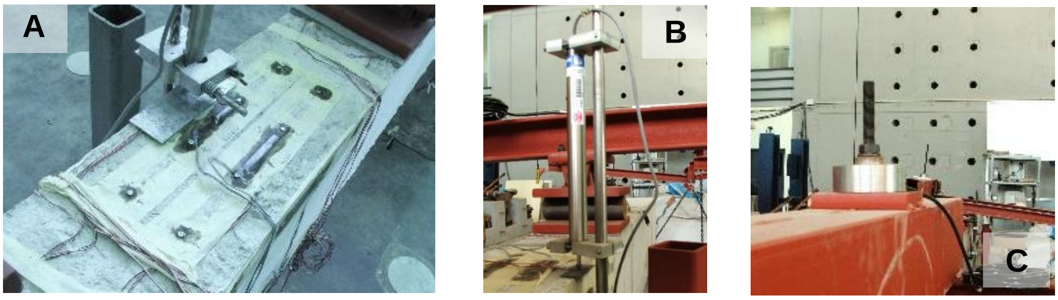


Fig. 7 Test instrumentation. A: Strain gauges on concrete beams. B: Displacement transducer. C: Load cell

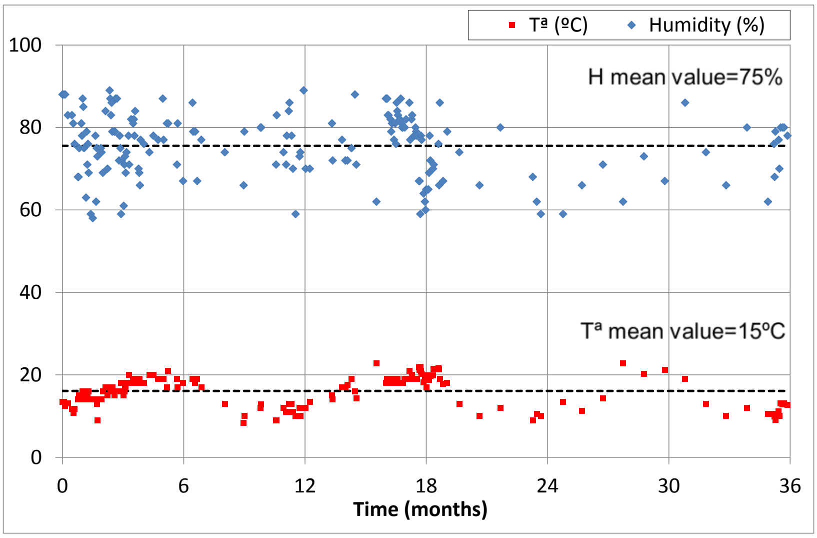


Fig. 8 Temperature and humidity conditions

4 RESULTS AND DISCUSSION.

The test under sustained load began with the loading process at a concrete age of 42 days (t_0) and continued for 1000 days. The sustained load was defined to obtain the objective stress (σ) that guaranteed elastic range behaviour at the most compressed fibre in the beam central section, and at the cylindrical specimens tested on the creep frame. This stress level was calculated as σ/f_c, with f_c being the experimental compressive strength at loading age. In order to maintain stresses in the elastic range, σ/f_c has to be less than 0.4.

4.1 Results

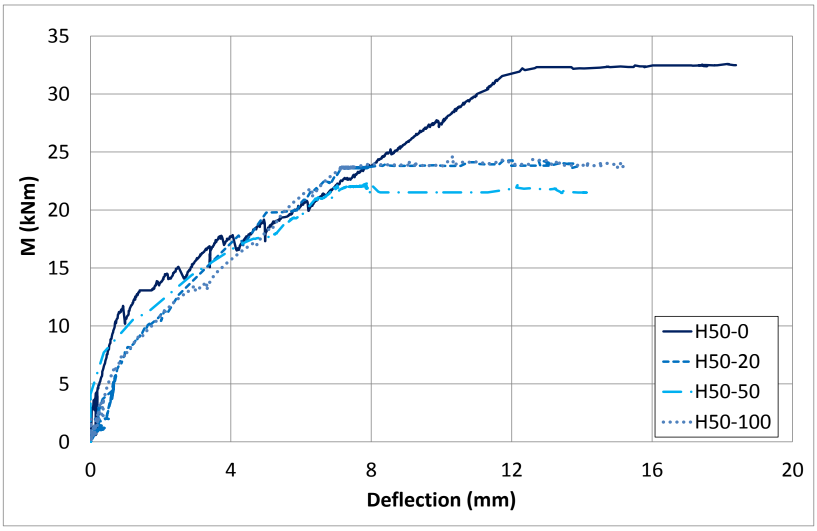
The moment-midspan deflection curves of the H50 and H65 series RC beams, obtained from the long-term tests under sustained load, are shown in Fig. 9. The ascending portion of these curves represents the loading process up to the bending moment related to the load (M_Q). The deflections then increase while the bending moment remains constant because of the sustained load for 1000 d.

The Test parameters and main experimental results are presented in Table 4:

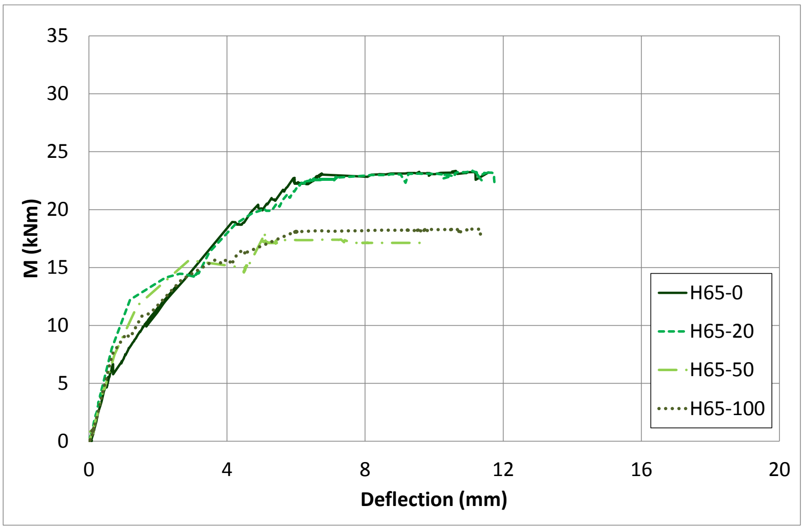
- Acting bending moment (M_Q), stress value (σ), and stress level (σ/f_c) generated at most compressed fibre in central section of RC beams.
- At loading age (t_0 = 42 d): immediate deflection at mid-span (δ_0), and concrete strain at most compressed fibre in central section of RC beams (ε_0).
- Cracking moment (M_{cr}) and deflection (δ_{cr}).
- Total deformations (δ (t-t_0=1000 d) and ε (t-t_0=1000 d)), and long-term deformations (δ_{dif} (t-t_0=1000 d) and ε_{dif} (t-t_0=1000 d)), at 1000 d.

Table 4 Stress, moments, deflections, and strains at mid-span of RC beams

		H65 series RC beams				**H50 series RC beams**			
		0%	**20%**	**50%**	**100%**	**0%**	**20%**	**50%**	**100%**
σ	MPa	14.19	13.43	10.34	9.80	21.92	16.09	14.15	14.79
σ/f_c	%	28	29	25	30	33	27	27	36
M_{cr} (cracking moment)	kNm	13.97	12.22	11.71	9.28	17.78	12.68	14.37	12.75
M_O (acting moment)	kNm	23.03	23.00	17.13	18.10	31.55	23.94	21.88	23.11
δ_{cr} (cracking deflection)	mm	1.92	1.59	1.40	1.08	1.74	1.57	1.22	1.20
δ_0 (immediate deflection)	mm	6.71	5.95	4.96	4.59	11.73	7.90	7.87	6.80
δ_{dif} (t-t_0=1000 days)	mm	4.87	5.86	4.67	6.75	6.66	5.97	6.21	8.40
δ (t-t_0=1000 days)	mm	11.58	11.81	9.63	11.34	18.39	13.87	14.08	15.20
ε_0 (t_0=42 days)	με	-433	-434	-327	-376	-442	-465	-472	-691
ε_{dif} (t-t_0=1000 days)	με	-583	-708	-669	-753	-893	-755	-770	-810
ε (t-t_0=1000 days)	με	-1016	-1142	-996	-1129	-1335	-1220	-1242	-1501



a) H50 series RC beams



b) H65 series RC beams

Fig. 9 Moment-midspan deflections

4.2 Loading process analysis: bending moments and deflections

The short-term behaviour was previously analysed using twin beams tested at 28 d up to failure, with a four-point bending test [53]. Therefore, in this loading process, cracking bending moments, M_{cr}, and acting moments, M_Q, were obtained. Furthermore, beam deflection related to the cracking moment, δ_{cr}, and that measured immediately after loading, δ_0, were also determined. These results are presented in Table 4.

The results from the analysis of the loading process indicated that, in general, similar trends were observed in both the recycled and conventional concretes, although deflections of recycled concretes with high replacement percentages were marginally greater than those of concrete with natural aggregate.

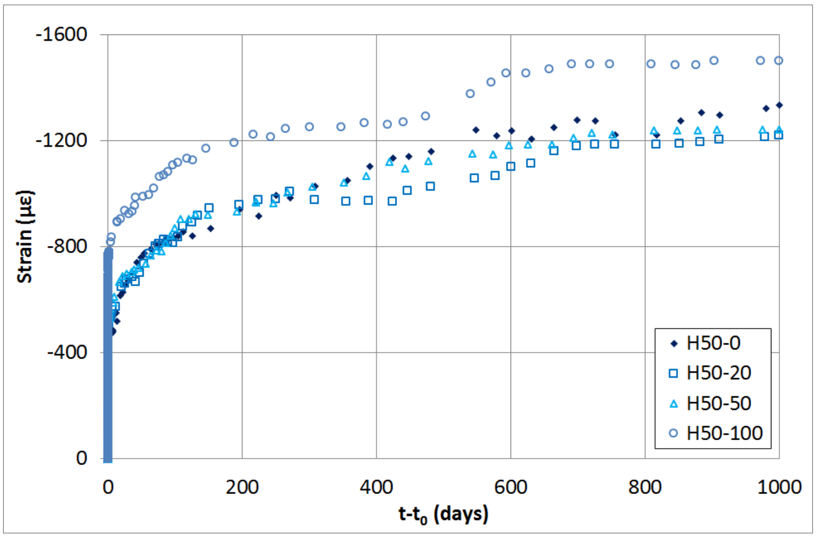
On the basis of the obtained results (Table 4), it can be stated that cracking moments are significantly reduced as the content of recycled aggregate increases. In comparison to conventional concrete, decreases of 28%, 19%, and 28% were measured for H50-20, H50-50, and H50-100, respectively. These reductions are 10%, 13%, and 26%, when H65 concretes are analysed. As expected, cracking behaviour is significantly influenced by the use of recycled aggregates [33,34].

4.3 Strain over time

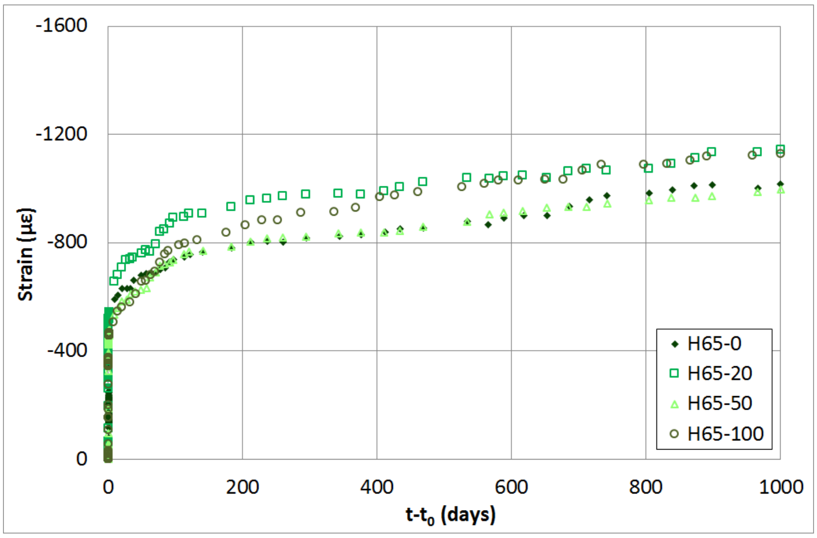
A long-term analysis of the cross section was conducted over 1000 d, using the experimental strains measured by concrete strain gauges, at the mid-span of RC beams, as shown in Fig. 10. It is observed that concrete strain develops primarily over the first 200 d, and then tends to stabilise, both in recycled and conventional concrete. Long-term strains were calculated as the difference between the strain registered at t days, and the immediate strain registered at t_0 days. In order to determine the influence of recycled aggregate on concrete strain, it was necessary to use specific deformations, calculated as the relationship between the measured concrete strain and the stress, because of the different stress value of each concrete. Figure 11 shows the 'specific long-term strain-time' curves at the compression zone of concrete beams over 1000 d.

From these results, it can be stated that the use of recycled coarse aggregate significantly influences concrete behaviour in terms of long-term deformations. This effect is more noticeable as the amount of recycled aggregate increases, as the mortar content is the main factor influencing concrete creep, and recycled concrete incorporates a high volume of this material because of the presence of old adhered mortar [16,21,22,54,55]. Compared to conventional concrete, the H50 series recycled concrete beams exhibited 15%, 34%, and 34% increases in long-term strains at 1000 d for replacement percentages of 20%, 50%, and 100%, respectively. These increases were 28%, 57%, and 87% for H65-20, H65-50, and H65-100, respectively.

Regarding the influence of the concrete series, the greater the water content, the lower the mechanical strengths and the greater the deformability in H65 series RC beams, compared to the H50 series, both in recycled and conventional concretes. Additionally, the recycled concrete of the H65 series develops greater strain increases as the recycled aggregate increases, compared to those with a lower ratio (H50). This can be seen in concretes with high replacement percentages, and specifically for a replacement ratio of 100%. This effect can be attributed to the high water to cement ratio introduced by the pre-saturation process of this concrete series.

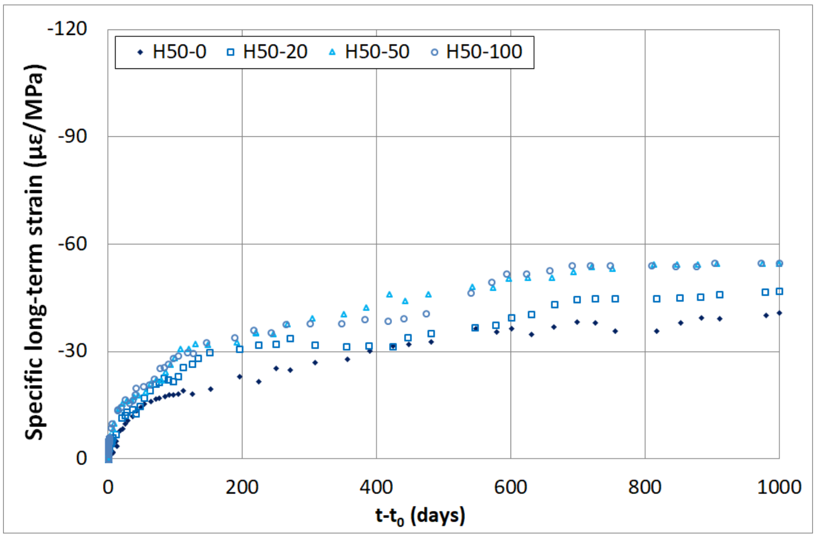


a) H50 series RC beams

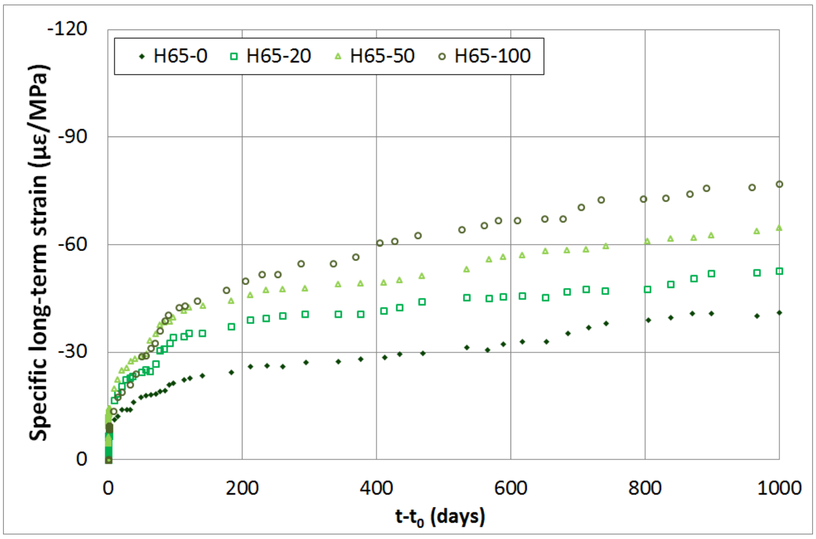


b) H65 series RC beams

Fig. 10 Strain-time at mid-span of beams



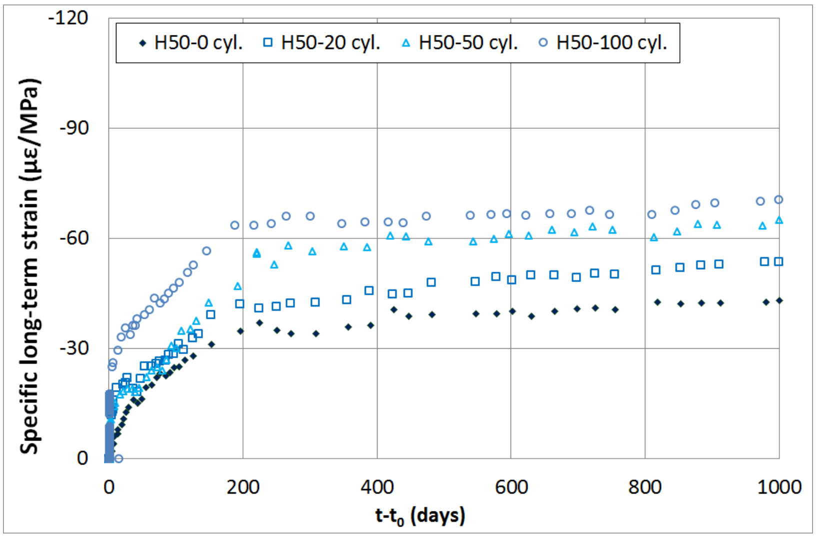
a) H50 series RC beams



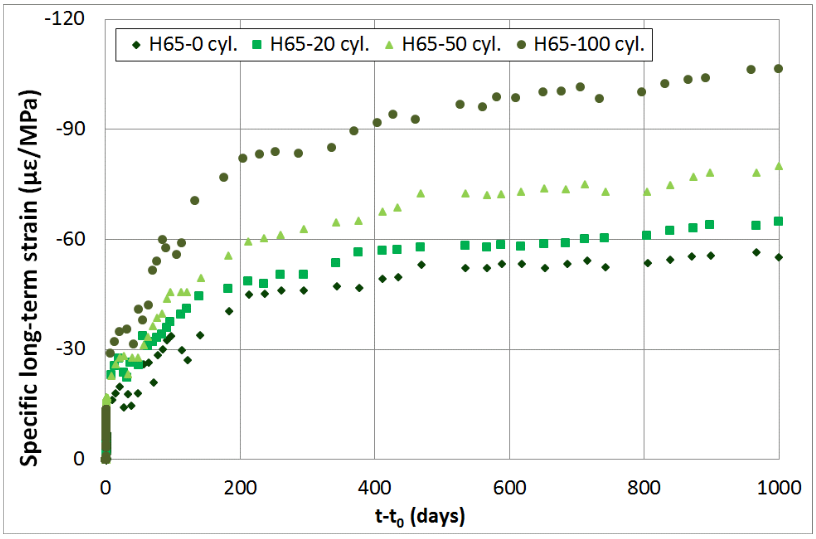
b) H65 series RC beams

Fig. 11 Specific long-term strain-time at mid-span of beams

The specific long-term strains are analysed by comparing them with those obtained using the cylindrical specimens from the creep study, shown in Fig. 12 [46]. As previously reported [46], although both curves exhibit a similar trend, the beam strains are lower than those of the cylindrical specimens, because of the restraining effect of reinforcing steel. Although RC strain is primarily attributed to creep, neglecting the shrinkage effect, the plain concrete strain takes into account strains from both stress and the shrinkage effect [56]. Therefore, it has been observed that recycled aggregate content influences long-term strains of plain concrete to a greater extent, than those of RC, again because of the effect of the reinforcing steel.



a) H50 concretes



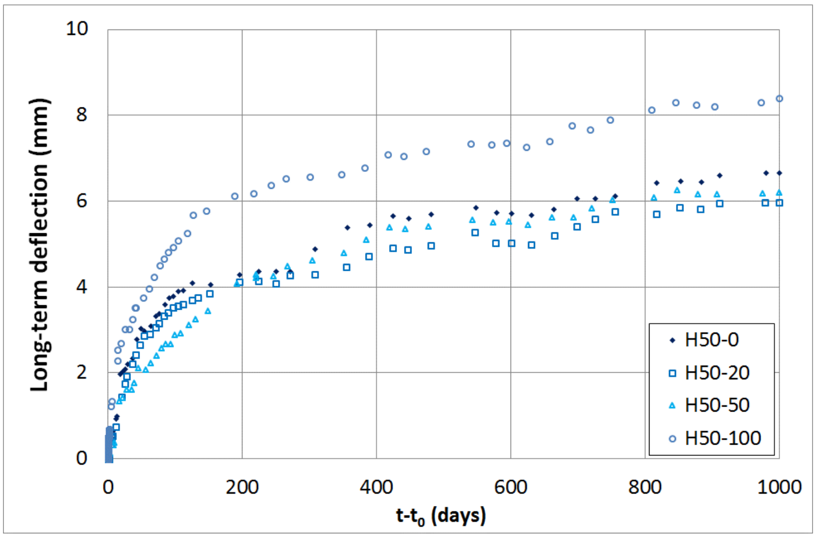
b) H65 concretes

Fig. 12 Specific long-term strains of cylindrical specimens

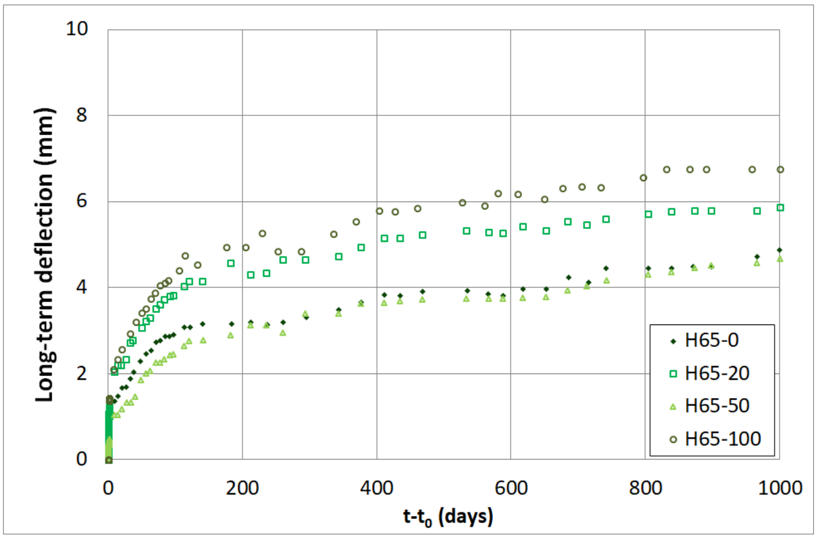
4.4 Long-term deflections

Beam deflections were measured over 1000 d by displacement transducers placed at the mid-span of the beams. As a time-dependent analysis of concrete strains, certain specific values of concrete deflections were included in Table 4, such as immediate deflection at loading age, t_0, of 42 d, total deflection, and long-term deflection at t-t_0 = 1000 d.

The long-term deflections-time curves obtained as the difference between the total deflection and immediate deflection, are shown in Fig. 13. These results exhibit similar trends to those of the concrete strains. Deflections increased primarily during the first 200 d of loading, in both the recycled and conventional concrete, and later, they exhibited smaller increases, and tended to stabilise over time.



c) H50 series RC beams



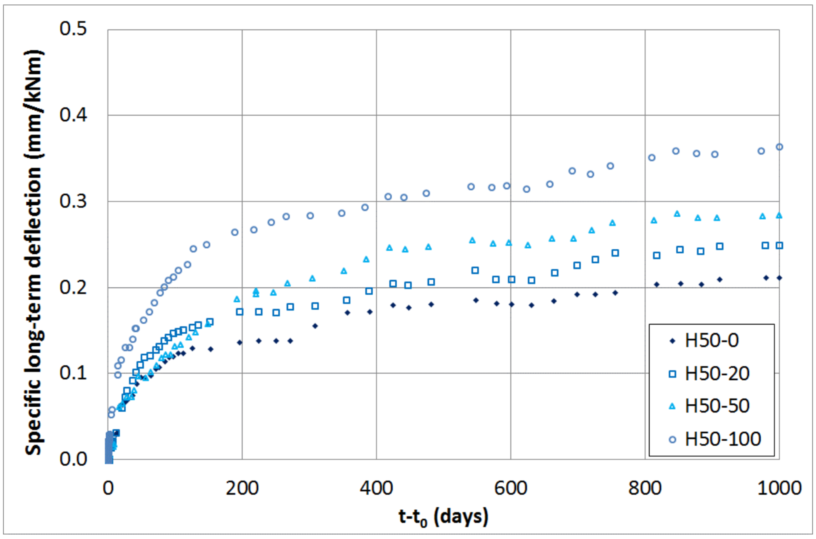
d) H65 series RC beams

Fig. 13 Long-term deflections-time curves

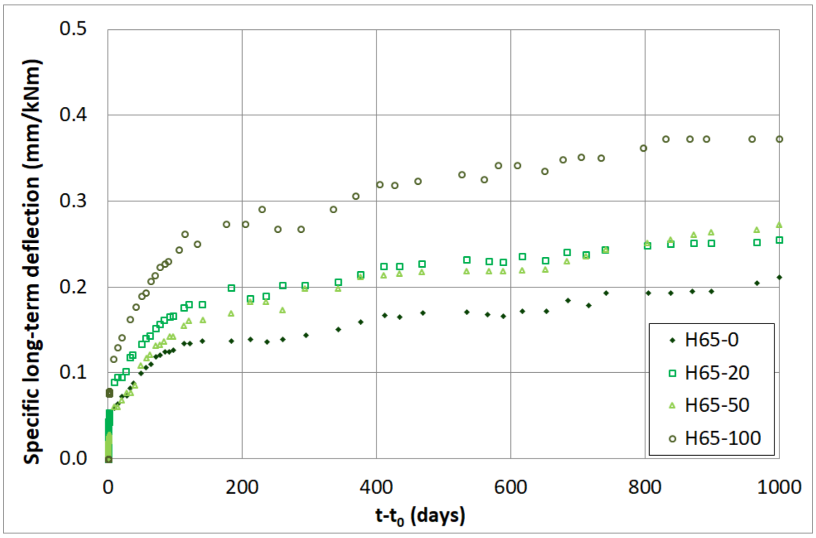
As was previously observed, the different stress values of each concrete made it difficult to establish comparisons between recycled and conventional concrete, taking into account the replacement percentages used. Therefore, in order to analyse the influence of recycled aggregate, long-term deflections were analysed using their specific values obtained as the relationship between the long-term deflections and the acting bending moments (Fig. 14).

According to the literature [42], the results reveal that recycled aggregate content has a significant influence on the specific long-term deflections of recycled concrete. This is because of the greater deformability of recycled concretes over time. The different time-dependent properties, shrinkage and creep, result in greater long-term deflections of recycled concretes, compared to conventional concretes.

Compared to conventional concrete, recycled concrete H65 exhibited 21%, 29%, and 76% increases in specific long-term deflections at 1000 d, with replacement percentages of 20%, 50%, and 100%, respectively. The specific long-term deflections of the H50 series exhibited a similar trend, with increases of 18%, 34%, and 72% for H50-20, H50-50, and H50-100, respectively. In this case, the H65 series RC beams exhibited similar specific long-term deflections to the corresponding H50 series RC beams. Therefore, the recycled concrete of the H65 series developed similar increases, in long-term deflections, to those obtained in the H50 series, with increasing recycled aggregate.



a) H50 series RC beams

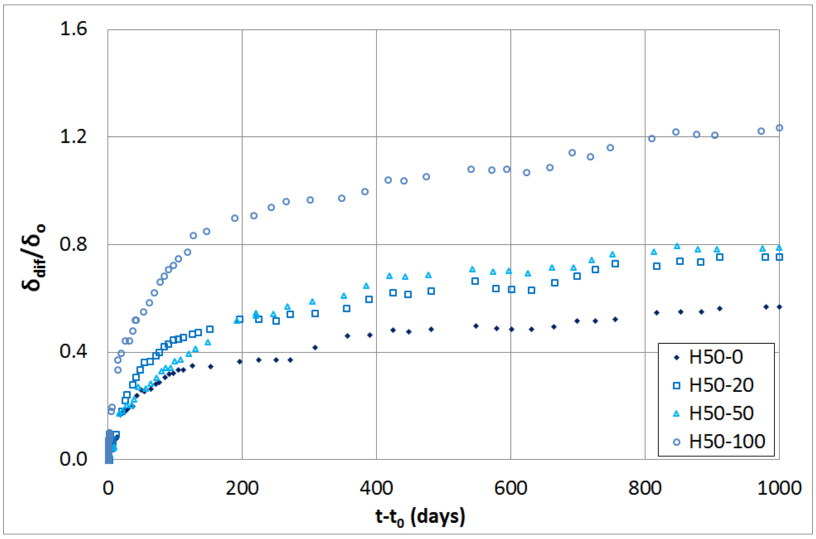


b) H65 series RC beams

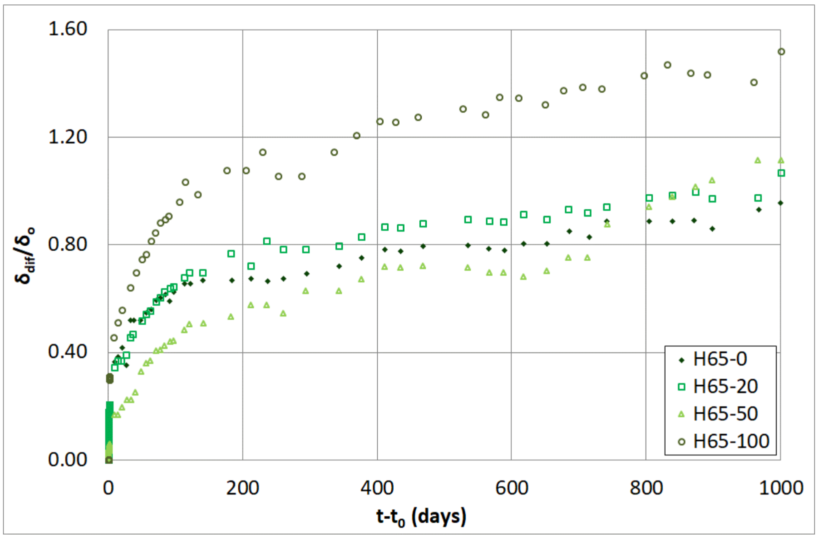
Fig. 14 Specific long-term deflections-time curves

The relationship between long-term and immediate deflections over time, for all concrete beams, is shown in Fig. 15. Compared to the results obtained by Choi et al. [43], it can be noted that recycled concrete ratios increase as the replacement percentage of recycled aggregate increases from 0.7–1.5. In previous studies, it was reported that no significant differences in immediate deflections are exhibited in recycled and conventional concretes [53]. This confirms that the long-term deflection of recycled concrete is greater than that of conventional concrete, and increases as the replacement percentage increases.

Additionally, these ratios are directly related to the creep coefficients (Fig. 3), which were analysed in previous studies [46]. However, the values of the ratios are lower than the creep coefficients determined from the cylinder tests. This is attributed to the use of reinforcing steel that restrains the free deformation of RC beams. Nonetheless, the long-term to immediate deflection ratio increases as the recycled aggregate content increases, as with the creep coefficients.



a) H50 series RC beams



b) H65 series RC beams

Fig. 15 Long-term and immediate deflection over time

Therefore, it can be stated that the creep coefficients, and shrinkage strains, of recycled concretes [21,46,55] have a significant influence on the long-term behaviour on the strains and deflections of structural recycled concrete. Therefore, the different time-dependent properties of recycled concrete have to be considered in structural designs.

5 PREDICTION OF LONG-TERM DEFLECTIONS

With the aim of analysing the suitability of current proposals for the calculation of long-term deflections in recycled concretes, different codes and standards have been evaluated. These can be divided primarily into two categories: expressions included in Eurocode 2 and International Federation for Structural Concrete (fib) Model Code 2010, which consider the effect of creep and shrinkage, and those that predict the long-term deflections based on the load duration and instantaneous deflection (Spanish and American standards [51,57]).

5.1 Prediction procedures

The Spanish and American standards [51,57] propose a method to calculate long-term deflections based on the immediate deflection caused by the sustained load, and a multiplier coefficient, λ, that is a function of the load duration and reinforcement ratio.

$$\delta \tag{1}$$

Where δ_{dif} is the long-term deflection due to creep and shrinkage; δ_o is the immediate deflection due to sustained load; and λ is calculated as follows:

$$\frac{\quad}{\quad} \tag{2}$$

Where ξ is a factor that is 2 for a load duration of 5 years or more, 1.4 after one year, 1.2 after 6 months, and 1 after three months.

The reinforcement ratio can be calculated as $\rho' = A_s'/bd$, where $A_s'$is the compression reinforcement area, and b and d are the width and effective depth of the concrete cross-section, respectively.

The immediate deflection is calculated with Branson´s equation, using the modulus of elasticity for concrete at loading age, E_c, and an effective moment of inertia, I_e, given by (3):

$$— \qquad — \qquad (3)$$

where is the moment of inertia of the gross, uncracked, concrete section, is the moment of inertia at the fully cracked section, is the cracking bending moment, and M is the bending moment from the sustained load at the midspan of the RC beam.

Alternatively, the long-term deflection may also be calculated as of the sum of the deflections that occur after the immediate deflection, from the sustained load, and the time-dependent concrete deformations [56,58–61]. As a result, long-term deflection is obtained by adding shrinkage induced deflection, δ_{sh}, and creep deflection, δ_{φ}).

$$(4)$$

The shrinkage induced curvature (k_{sh}), depends on the shrinkage strain, ε_{sh}, the relationship between the modulus of elasticity of reinforcing steel and concrete, $n = E_s/E_{c,eff}$, and the sectional properties where the long-term deflection is calculated, where S is the first moment of section, and I is the moment of inertia.

$$- \qquad (5)$$

Where $E_{c,eff}$ is the effective modulus of concrete given by:

$$— \qquad (6)$$

For a simple beam of span l, the deflection at mid-span due to shrinkage is:

$$- \qquad (7)$$

The creep deflection is the product of the immediate deflection, δ_o, from the sustained load, and the creep coefficient, φ.

$$(8)$$

It was noted that, in this method, the creep coefficient and the shrinkage strain of concrete at different ages after loading ($t-t_o$) are required.

Regarding the immediate deflection, it can be obtained by the bilinear model specified in Eurocode 2 and fib Model Code 2010 [58,59]. It is known that typical service conditions lead to the cracking of concrete members, so an accurate design must involve the analysis of cracked concrete. However, if the analysis assumes the fully-cracked condition, deflections will be overestimated. On the other hand, if every cross-section is assumed to be uncracked, deflections will be underestimated. Therefore, because of the contribution of tensile concrete to the member stiffness, known as tension stiffening, the deflection of a partially cracked beam lies somewhere between the cracked and uncracked conditions [61]. Consequently, this approach uses a distribution coefficient, ζ, to interpolate both states, cracked and uncracked, involving the effect of tension stiffening.

(9)

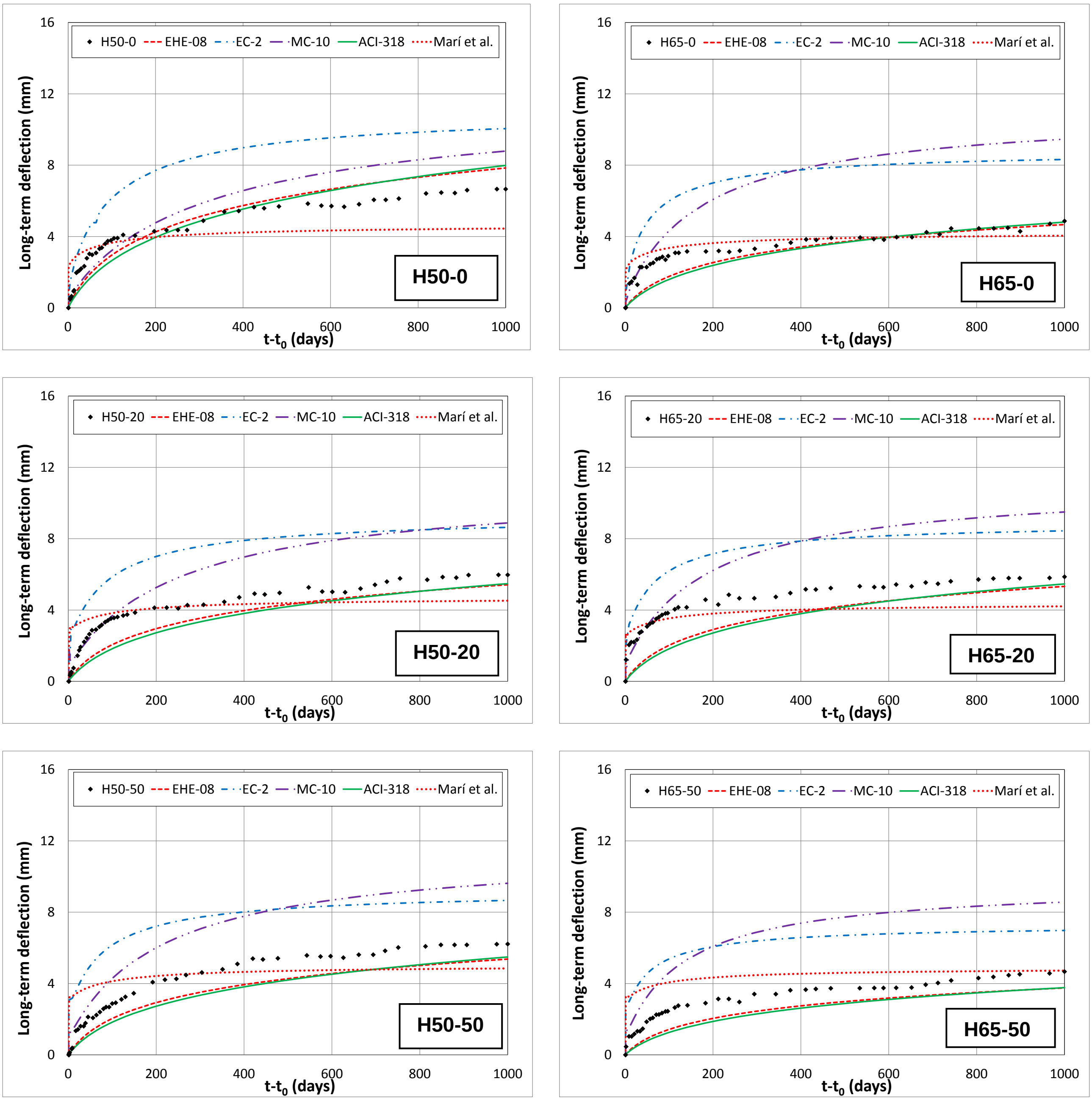
where δ_{cr} is the cracked deflection, δ_{uncr} is that part of immediate deflection that occurs before cracking, and ζ is given by:

— (10)

However, all of these procedures require different concrete properties, including E, f_{ct}, φ, and shrinkage strain. These properties can be experimentally obtained, or calculated according to code-based equations, using only the compressive strength. However, numerous researchers have reported that some of these code equations cannot be used when recycled concrete is considered, because of it exhibiting lower moduli of elasticity and splitting tensile strengths, greater strains from creep and shrinkage, and different time-dependent development in comparison to conventional concrete [16,22,46,55,62,63]. In order to consider the recycled aggregate effect, these concrete properties have to be calculated either experimentally, or using the modified expressions proposed in previous studies [45,46,64].

5.2 Calculated deflections *vs.* experimental deflections

On the basis of existing procedures [51,57–60], long-term deflections have been calculated at different ages, and compared with those experimentally measured (Fig. 15). As discussed above, the prediction of long-term deflections according to code-based expressions involves short-term deflection, shrinkage induced deflection, and creep deflection. Each of these parameters is calculated using the specific concrete properties of tensile splitting strength, modulus of elasticity, creep coefficient, and strain due to shrinkage, which are significantly affected by the recycled aggregate content. In order to consider the recycled aggregate effect, these concrete properties are obtained using the modified expressions proposed in previous studies [45,46,64]. The procedure to calculate long-term deflections of recycled aggregate concretes using experimental compressive strength, taking into account the corrections discussed above, is shown in Fig. 16.



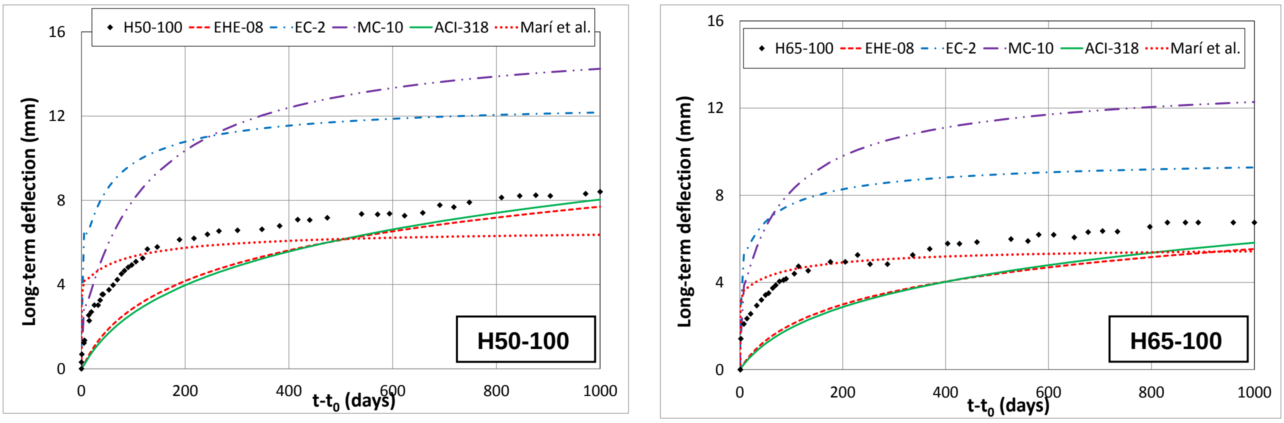


Fig. 15 Long-term deflections at different ages, calculated from existing procedures [51,57–60] and experimental results

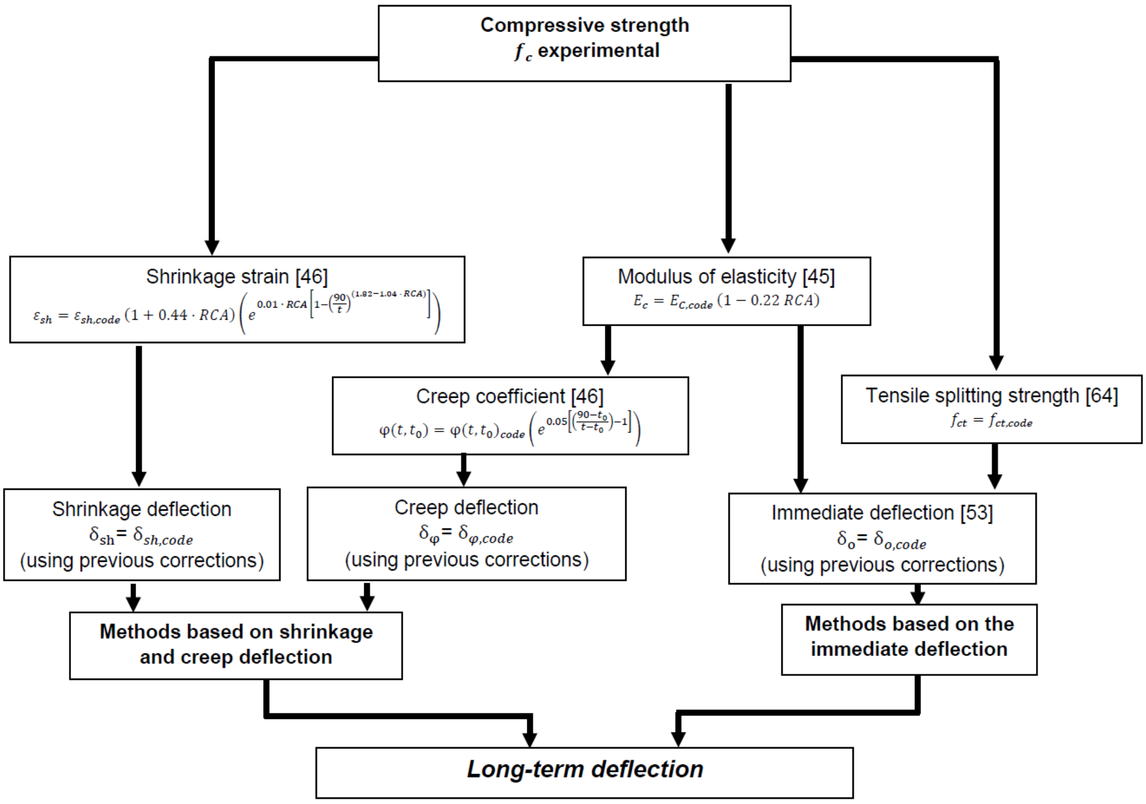
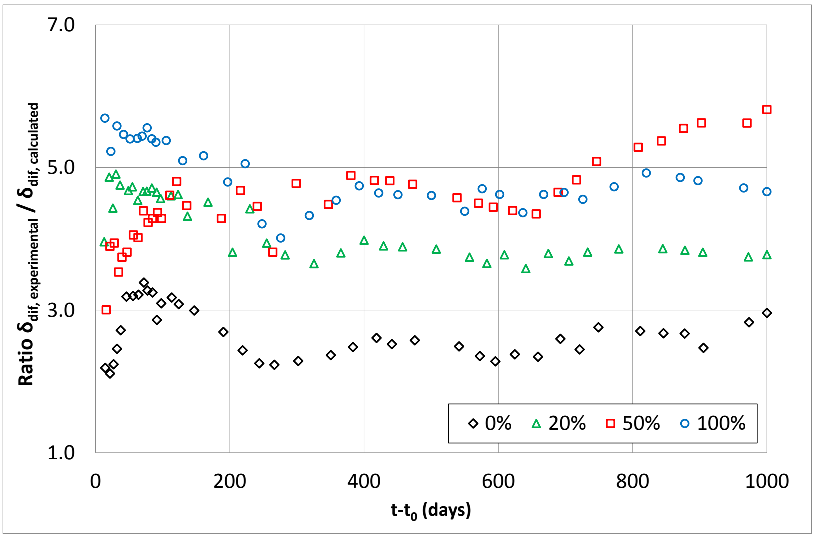
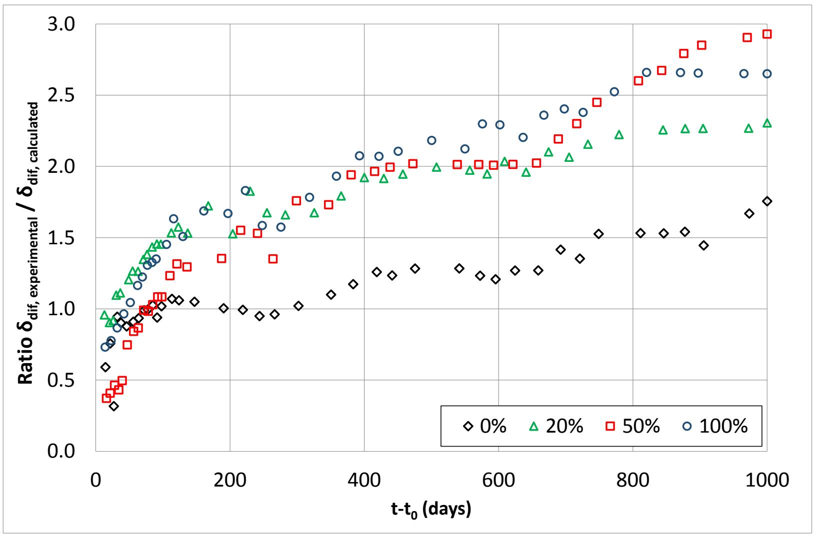


Fig. 16 Procedure to calculate long-term deflection of recycled aggregate concrete

The code-based expressions yield different results, depending on whether or not the shrinkage strain and creep coefficient [58–60] are used [51,57]. It should be noted that prediction procedures ACI 318 and EHE-08 provide similar predictions, as the same method was used. However, when the induced shrinkage deflection and creep deflection were considered by Eurocode 2 and fib Model Code approaches, different accuracies were obtained. In order to analyse these differences and assess if any correction is required to predict long-term deflections of recycled concrete, the 'experimental long-term deflection/calculated long-term deflection' ratios were calculated as an average of both concrete series (Fig. 17).



a) Spanish and ACI 318 approach



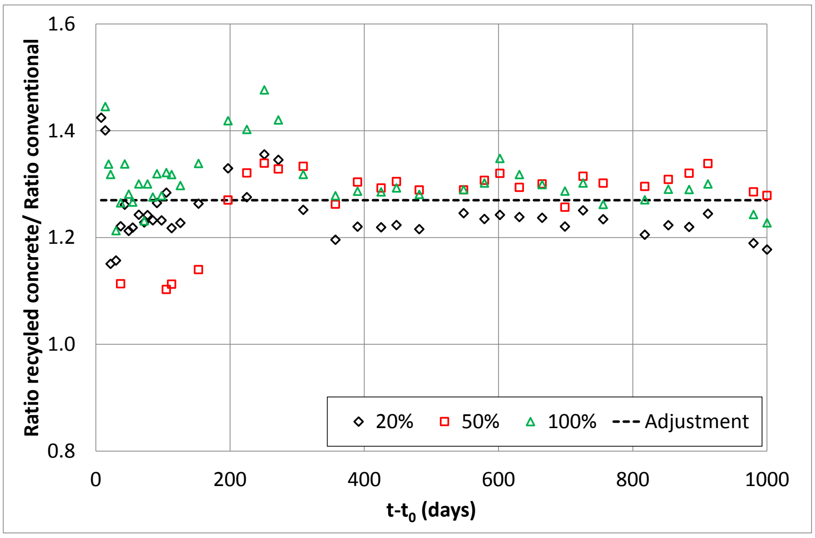
b) Eurocode 2 and fib Model Code approach

Fig. 17 Experimental long-term deflection/calculated long-term deflection ratios over time

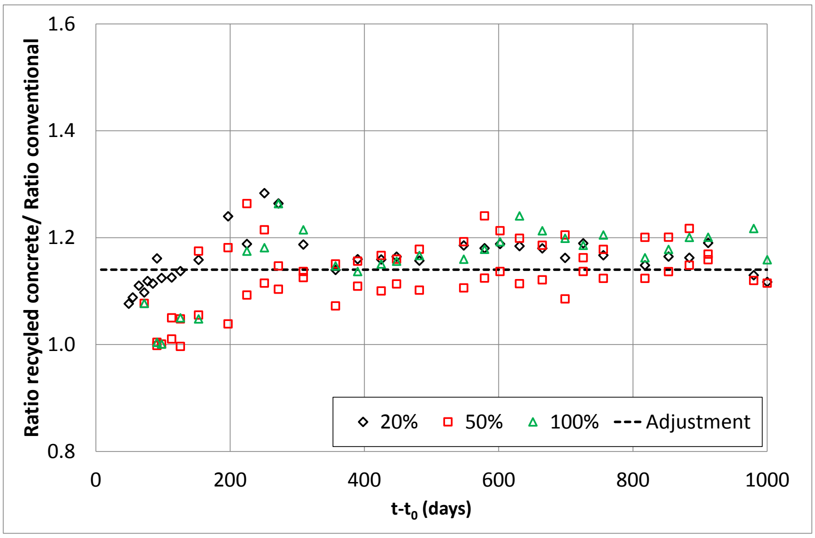
On the basis of these results, it can be stated that recycled concrete provides marginally greater ratios than conventional concrete, although the results do not show any significant influence from the replacement percentage. However, it can be noted that these ratios are different, depending on the prediction procedure, and exhibit a greater influence of recycled aggregate when they are obtained using methods based on immediate deflection in comparison to other prediction procedures.

Therefore, in order to calculate the long-term deflection of recycled concrete with the same approximation degree as that of conventional concrete, according to the method of calculus used, it is necessary to propose a modified equation. Accordingly, two different coefficients were adjusted by regression analysis, using the relationship between the ratios of recycled and conventional concrete previously obtained, as shown in Fig. 18. These coefficients were calculated as follows:

$$\rightarrow \qquad (11)$$



a) Spanish and ACI 318 approach



b) Eurocode 2 and fib Model Code approach

Fig. 18 Experimental long-term deflection/calculated long-term deflection ratios over time

The coefficient will be 1.27 if the long-term deflection is calculated according to the method proposed in the Spanish and American standards [51,57], and 1.14 if the shrinkage induced deflection and creep deflection are considered according to Eurocode expressions [58–60].

Simplified method of Spanish and American standards [51,57]:

Methods based on creep and induced shrinkage deflection [58–60]:

In order to assess these adjustments, some statistical indices were calculated. In this case, these proposals were evaluated using two statistical indices: the mean squared error (MSE), and the mean average error (MAE). As a result, the proposed coefficients provide values for those statistical indices which are lower than those calculated using the code expressions. The MSE decreases by 5% (from 0.041 to 0.039) when the Eurocode-based proposal is used in place of the current expression, and by 52% (from 2.362 to 1.137) when the EHE-modified expression is considered. Regarding the MAE, the values decreased by 7% (from 0.160 to 0.149) for the Eurocode correction, and 38% (from 1.113 to 0.693) for the EHE proposal. Therefore, it can be stated that the proposed coefficients improve the prediction of long-term deflections in recycled aggregate concretes, compared to the results obtained when current code-based expressions are used.

Finally, it can be concluded that long-term deflections of recycled aggregate concrete can be accurately calculated at different ages, using the abovementioned structural methods, corrected with the proposed coefficients. These proposals take the effect of the recycled aggregate content into consideration when using the concrete properties obtained, according to the previously proposed expressions for the tensile splitting strength, modulus of elasticity, shrinkage strains, and creep coefficients [45,46,64], with only the values for the compressive strength and replacement percentage of each concrete being used as initial data.

6 CONCLUSIONS

In this study, the long-term flexural performance of recycled aggregate concretes was determined, and the following conclusions were drawn:

- The long-term deformation (strains and deflections) developed similarly in all concretes. The recycled and conventional concretes developed the most deformations during the first 200 d. The strain curves tended to stabilise after that time.

- The use of recycled coarse aggregate significantly influenced the long-term deformations (strains and deflections). The greater creep coefficients and shrinkage strain, of recycled concretes, had a significant influence on the long-term behaviour of structural recycled concrete. Therefore, the different time-dependent properties of recycled concrete need to be considered in structural designs.

- According to code expressions, long-term deflections were predicted at different ages, and in order to determine the suitability of proposing corrector coefficients for these expressions, the ‘experimental long-term deflection/ calculated long-term deflection’ ratios were obtained. As a result, it was noted that, in order to maintain the same ratios in conventional and recycled aggregate concretes, a correction factor was required.

- The proposed factor was adjusted, with 1.27 used when using the Spanish and American standards [51,57], and 1.14 when using the induced shrinkage deflection, and creep deflection was considered [58–60]. These coefficients multiply the long-term deflection calculated using the different code-based expressions, taking into account the compressive strength of concrete, and the previously proposed expressions, to determine tensile splitting strength, modulus of elasticity, shrinkage, and creep coefficient [45,46,64].

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The authors declare that they have no conflict of interest.

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