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Deformation recovery of reinforced concrete beams made with recycled coarse aggregates

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ABSTRACT

The purpose of this research is to analyse the long-term deformations of reinforced concrete beams made of recycled coarse aggregates (RCA), using four different replacement ratios, 0%, 20%, 50% and 100%. For said purpose, three different loading stages were carried out: firstly, loading and sustained load for 1300 days, secondly, unloading and recovery where the deformations were registered over a one year period, and lastly, testing the concrete beams up to failure in order to analyse the effect of recycled aggregates on pre-cracked concrete members. The results led to the analysis of deformations under sustained load, as well as those produced after removing the load and the performance of pre-cracked members, while identifying the effect of recycled coarse aggregates on concrete performance in terms of plastic deformation, recoverability and concrete stiffness, and also on structural design.

1. Introduction

In recent years, the use of construction and demolition waste as aggregates for structural concrete has been widely studied. Numerous authors have contributed to the increasing knowledge in this field, analysing the structural performance of recycled concrete and its properties, such as mechanical strength, modulus of elasticity, creep and shrinkage or durability [1-3]. As a result, several expressions and methods have been assessed for the design of structural concrete using recycled aggregates [4-12]. Most authors deal with the short and long-term behaviour of concrete while considering only the influence of creep and shrinkage [13-15] and very few include the ageing effect of concrete, its different cracking behaviour or its ability to recover from deformations after a load is varied or removed [16].

As common concrete structures are usually submitted to load variations during their service life, it is important to consider the effect of creep over time, including not only loading periods but also unloading the stages and the recoverability of concrete. As mentioned by Rossi et al. [17] understanding the behaviour of concrete structures is greatly simplified by the numerical modelling of their mechanical behaviour. However, progress needs to be made to predict the long-term behaviour of concrete with sufficient accuracy. In order to determine the deformational mechanism, it is also important to analyse the effect of cracking and residual strain i.e. the irreversible part of strain. Many factors influence deformation and the ability of concrete to recover after unloading. Once the hysteretic recovery has finished, the residual deformation can be defined as plastic deformation. Additionally, it can be assumed that concrete deformations under loading are mainly due to creep, especially for long periods of loading and therefore, the ability of deformations to recover after unloading is closely linked to creep recovery.

In this regard, some authors [18,19] concluded that creep recovery is independent of loading age and duration while others [20,21] disagreed completely with this assumption saying that it is influenced by both factors. Jensen [20] attributes this effect to the concrete hydration process which tends to slow as the loading age increases. When the loading age is too early or load duration too short, the internal micro-cracking continues to grow before the hydration process ends and this results in greater creep recovery. When the hydration of the concrete has almost stopped the internal micro-cracking no longer occurs, and the creep recovery decreases. Additionally, Mei et al. [21] consider not only the effect of the hydration process of concrete but also the fact that the strain produced for a short load duration is mainly due to elastic deformation and will be not recoverable. Mei et al. [21] also found that concretes with higher strength show lower proportions of recoverable creep and this effect gradually reduces with load duration. It can be

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stated that a longer loading time leads to smaller proportions of recoverable creep deformation.

Regarding other factors such as humidity conditions and specimen size, Neville [22] and Muller [23] noted that these parameters do not affect the creep recovery of concrete. In contrast to creep development, creep recovery is relatively small and tends to stabilise quickly. Bazant and Kim [24] stated that the elastic modulus of concrete after unloading is slightly larger than that of the specimen at the same age with no loading, which greatly depends on the loading age. Therefore, the time-dependent evolution of strength and the elastic modulus under sustained load are not usually considered [21]. However, it is certainly important to consider the effect of cracking for calculations under service conditions, as significant errors will arise if these effects are not included when evaluating deformations and stresses under these conditions [25]. Cracks occur in reinforced members when the stresses exceed the tensile strength of concrete. After cracking, the internal forces in a section at the crack location must be resisted by the reinforcement and the uncracked part of the cross-section (stiffness of the member). When cracked sections are analysed, the part of concrete in tension is ignored and the effective section is considered, taking into account the neutral axis and the depth of the compression zone [26]. Tension-stiffening can be attributed either to tensile reinforcement (steel-related model) or concrete (concrete-related model). In the latter approach, it may be assumed that tension-stiffening is effective either in the whole tension area or the specified zone (close to reinforcement), called the effective area. This can be evaluated by comparing results from both pre-cracked and uncracked structures.

Regarding uncracked sections, it can be stated that reinforcement steel and concrete undergo compatible strains. Furthermore, the stress in the concrete has not yet exceeded its tensile strength and cracks do not occur. It is worth noting that the bond between the concrete and the reinforcing bars restrains the elongation of the steel and thus a part of the tensile force in the reinforcement at a crack is transmitted to the concrete between cracks. Therefore, the structural analysis of concrete members will be influenced by the bond behaviour of the concrete and the tension stiffening in the cracked stage. Ignoring the effect of tension stiffening in cracked stages results in the overestimation of deflections or crack width. Additionally, different authors [27,28] have analysed the influence of bond behaviour on concrete performance, especially in terms of cracking response, and proposed [28] the use of a bond factor β, that represents the ratio of average tensile stress in concrete and the cracking stress, in order to consider the effect of this bond behaviour on structural concrete. Recycled concrete is expected to display differences in this regard as its behaviour is worse in terms of cracking and bond performance [5,13,14]. Therefore, it is necessary to consider not only the influence of recycled aggregate on mechanical strength and the deformational behaviour of concrete but also its effect on bond behaviour and cracking performance.

The presence of the reinforcing bars usually contributes to reducing the effects of recycled aggregates on the structural performance of concretes, especially in terms of deformations [13]. The design type of concrete structures, ductile or brittle, is also a key factor to be considered in their structural analysis. In order to simplify the structural calculation, codes and design methods usually set purposes and establish hypothesis based on the deformational or bond behaviour of concrete. Most design procedures for concrete structures include methods based on age-adjusted stiffness or modulus, which take into account the time-dependent evolution of concrete properties and different parameters related to bond performance, cracking behaviour and stress–strain curves [29,30].

As recycled concrete displays a different performance in terms of long-term properties, deformation, bonding and cracking, it is necessary to analyse all of these parameters together in order to establish the relationship between them and the influence of the recycled aggregate content in terms of structural response.

2. Research significance and objectives

In order to promote the use of recycled concrete in the design of structural members, it necessary to determine the main factors influencing the structural performance of concrete and how these factors are affected by the use of recycled aggregates. Although some authors have developed models and proposed expressions for designing structural concrete with recycled aggregate, few have analysed the long-term performance or time-dependent behaviour of recycled concrete [13,31-34] and work considering the recoverability of these concretes after removing or varying loads is scarce [16,35]. As a concrete structure usually withstands different loading stages during its service life, the structural analysis must consider the values of permanent deformations and the ability of deformations to recover. Therefore, in order to take these effects on the structural design into account, it is necessary to analyse the different performances of recycled concrete in this regard, especially those with a high content of recycled aggregates.

This study aims to increase the knowledge in this field and provide results and conclusions in terms of long-term deformations of reinforced concrete beams made using different replacement percentages of recycled coarse aggregates (RCA), considering not only deformations under sustained load but also those produced after removing the load. It also looks at the performance of pre-cracked members considering the effect of the bond and cracking performance of recycled concrete. For said purpose, three different loading stages were carried out: firstly, loading and sustained load for 1300 days, secondly, unloading and recovery of deformations which were registered over a one year period, and lastly, testing the concrete beams up to failure in order to analyse the effect of recycled aggregates on pre-cracked concrete members.

3. Experimental program

This work is part of a long research project aimed at carrying out an in-depth analysis of the flexural performance of structural recycled concrete. Shrinkage, creep and flexural behaviour have already been evaluated in previous works [36-39]. For said purpose, two series of eight reinforced concrete beams were made with different replacement percentages of RCA. One of these series was loaded up to failure at 28 days in order to analyse the short-term behaviour of reinforced concrete beams [14]. The other eight twin RC beams were subjected to sustained load at t_0 (42 days) for 1300 days ($t_1 = 1342$ days) in order to evaluate the long-term performance of recycled aggregate concrete (Stage 1) [13]. In this part, creep and shrinkage were also determined and analysed using cylinder and prismatic specimens [39]. Lastly, these concrete specimens were unloaded (t_1) and deformation recovery (concrete deflections and strains) was registered for one year (t_2-$t_1 = 320$ days) in order to assess the behaviour of recycled concrete in terms of deflection and strain recovery (Stage 2). Finally, these reinforced concrete beams were tested up to failure (Stage 3), to analyse the effect of recycled aggregate on pre-cracked members. Fig. 1 summarises different loading stages.

3.1. Concrete specimens

Two concrete series were analysed, one with a water to cement ratio of 0.50, and another of 0.65, named H50 and H65, respectively. Each series consisted of four types of concrete, three of them were made using different replacement percentages for conventional coarse aggregate with recycled aggregate (20%, 50% and 100%), and the other with 0% replacement in order to obtain a baseline concrete. As a result, eight different concretes were designed and named H50-0, H50-20, H50-50, H50-100, H65-0, H65-20, H65-50 and H65-100. Table 1 lists mix proportions of these concretes.

All concrete specimens were cured with a soaked burlap for 48 h after casting. Then, they were stored at the laboratory up to the testing age, where the average temperature was 15 °C and average humidity

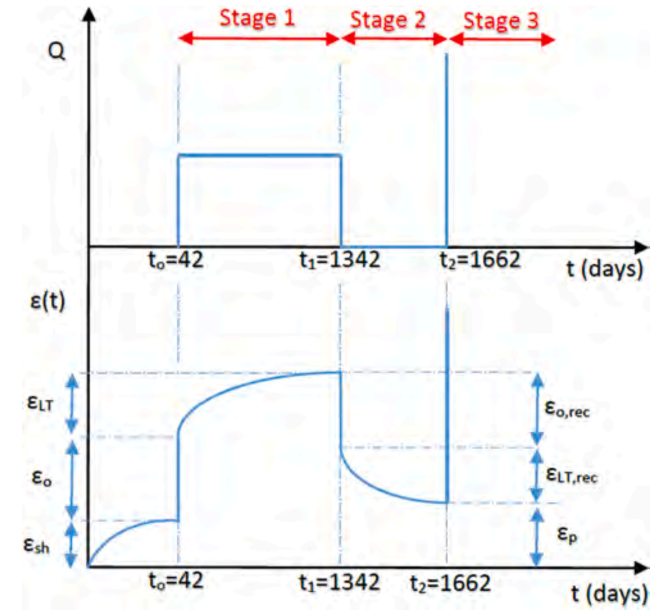


Fig. 1. Loading stages ε_{sh} = *shrinkage strain,* ε_o = *instantaneous strain,* ε_{LT} = *long-term strain due to creep and shrinkage,* $\varepsilon_{o,rec}$ = *instantaneous strain recovery,* $\varepsilon_{LT,rec}$ = *long-term strain recovery,* ε_p = *permanent strain.*

75%.

In order to carry out the experimental program, a large amount of different specimens were made to characterise the concrete and determine mechanical strength, modulus of elasticity, creep and shrinkage [39]. Then, two reinforced concrete beams (of each concrete) were prepared for structural tests, one for the short-term test and the other one for the long-term test [13,14]. This manuscript analyses the results obtained in the latter (long-term tests), that includes the loading process, sustained load period, unloading stage, recovery period and testing up to failure after all of these loading stages. In addition, the results of the reinforced concrete beams up to failure will be compared with those obtained in short-term tests, to analyse both cracked and uncracked beams.

The RC beams have been designed to analyse the flexural performance of reinforced concrete with RCA at different stages over time. Each one has a rectangular cross section of 30x20 cm (height × width), a length of 360 cm and a single span of 340 cm (Fig. 2.). They have been designed according to structural codes [40,41] taking the customary serviceability conditions into account. The reinforcement has been designed to obtain a ductile mode of failure. The design of these reinforced concrete beams has been more thoroughly detailed in previous papers [13,14].

3.2. *Test setup and instrumentation*

As aforementioned, the experimental program is divided into three different parts. The first stage consisted of maintaining a sustained load over time at simply-supported reinforced concrete beams, using a four-point bending test that generates a constant bending moment at the midspan of each beam. In order to evaluate not only the performance of reinforced concrete but also the response of plain concrete in terms of strain, the specimens and beams were tested simultaneously. The sustained load applied to the beams was also transmitted to a creep frame placed under the laboratory slab with two cylindrical specimens in which strains and load were also registered. The loading process and test setup is shown in Fig. 3 and it has been more thoroughly explained in previous research [13,39].

Table 1
Mix proportions 1 $m^{3.}$

		H50-0	H50-20	H50-50	H50-100	H65-0	H65-20	H65-50	H65-100
Cement	kg	380.00	380.00	380.00	380.00	275.00	275.00	275.00	275.00
Water	kg	190.00	190.00	190.00	190.00	178.75	178.75	178.75	178.75
0–4 N*	kg	781.43	781.43	781.43	781.43	918.49	918.49	918.49	918.49
8–20 N**	kg	665.44	532.35	332.72	0.00	486.19	388.95	243.10	0.00
4–12 N***	kg	307.93	246.34	153.97	0.00	457.65	366.12	228.83	0.00
4-16R****	kg	0.00	173.07	432.68	865.36	0.00	168.84	422.10	844.20
w/c		0.5	0.5	0.5	0.5	0.65	0.65	0.65	0.65
Admixture	%	0.85	1.2	1.07	1	0.85	1.2	1.07	1

*0–4 N: natural sand from crushed limestone. Water absorption (WA): 2.2%.
**8–20 N: natural coarse aggregate from crushed limestone. WA: 1.3%.
***4–12 N: natural coarse aggregate from crushed limestone. WA: 2.2%.
****4–16 R: recycled coarse aggregate from demolition of concrete structures. WA: 5.4%.

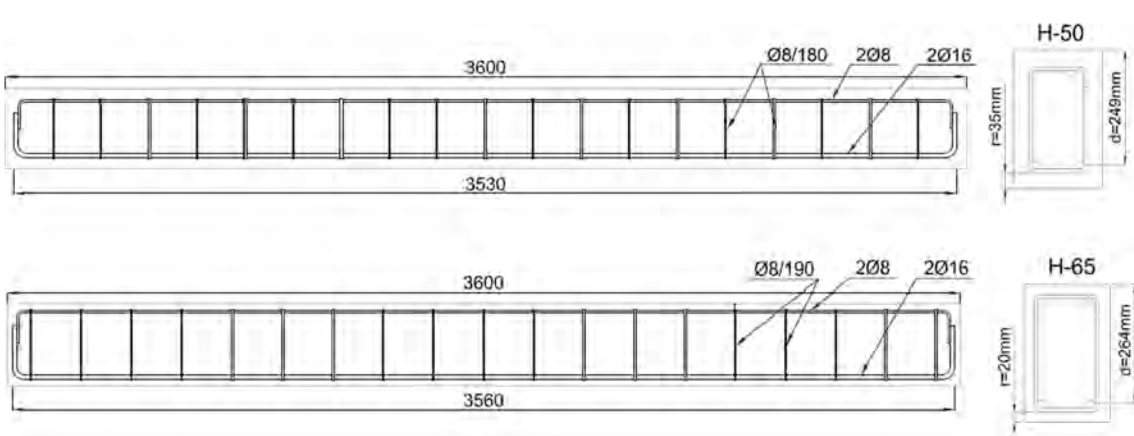


Fig. 2. Beam specimens (mm) [13,14]. **Reinforcement steel: B500SD, Es: 210000 MPa.*

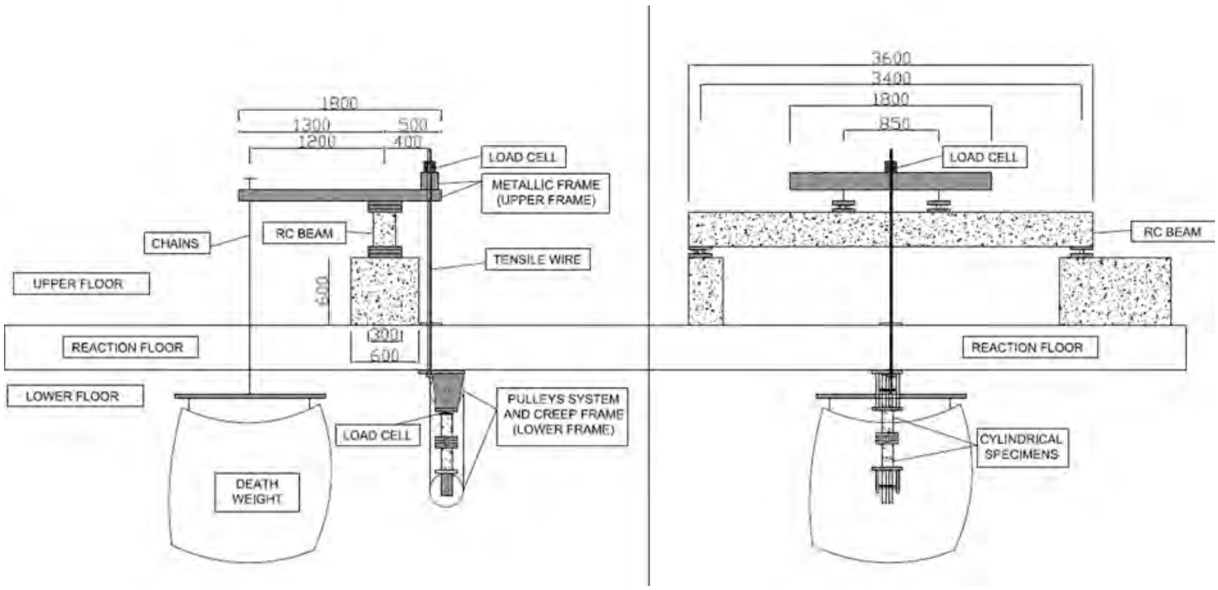


Fig. 3. Test setup of 1st stage: sustained load over time [13].

The load was applied at a concrete age of 42 days (t_0) and lasted for 1300 days. The sustained load applied was established according to the compressive strength of each concrete in order to perform this test within the elastic range of concrete. To perform this test, a lever system was used applying the load through a metal frame with a dead weight hanging at one end and the other end fixed by a tensed tie rod to the load slab, as can be seen in Fig. 3. The value of the load was calculated to obtain a maximum stress at the compression chord of the beam's midspan and at the creep specimens that was about 30% of the experimental compressive strength, i.e. $\sigma/f_c = 0.3$. To perform this test in the cylindrical specimens and in the concrete beam simultaneously, a pulley system was used with a tie rod that generated a compression force on cylindrical specimens located at the core of a creep frame under the load slab on which it was supported. This produced at the same time, a similar strain at the compression chord of the beam's midspan.

The second stage starts at a concrete age of 1342 days (t_1). At this time, the concrete specimens were unloaded and all concrete strains and deflections were registered for a period of 320 days, in order to determine not only the recovery of instantaneous deformations but also the recovery of long-term deformations. After this period, concrete beams were loaded up to failure using a four-point bending test with a displacement rate of 1.5 mm/min (stage 3). The geometry of the test was the same as in stage 1 and as that used in the short-term test at 28 days (Fig. 4). The use of the same test setup enables the responses of concrete in different loading processes over time to be compared, and the influence recycled coarse aggregates have on flexural stiffness to be determined.

Concrete strains and deflections were measured at the mid-span of the concrete beams through concrete gauges and a displacement transducer (LVDT), respectively (Fig. 5). This experimental data was recorded through a data acquirement system.

All tests were carried out under the same hygrometric conditions at the laboratory, i.e. under an average humidity of 73% and an average temperature of 14 °C. At all stages, the load applied was registered using

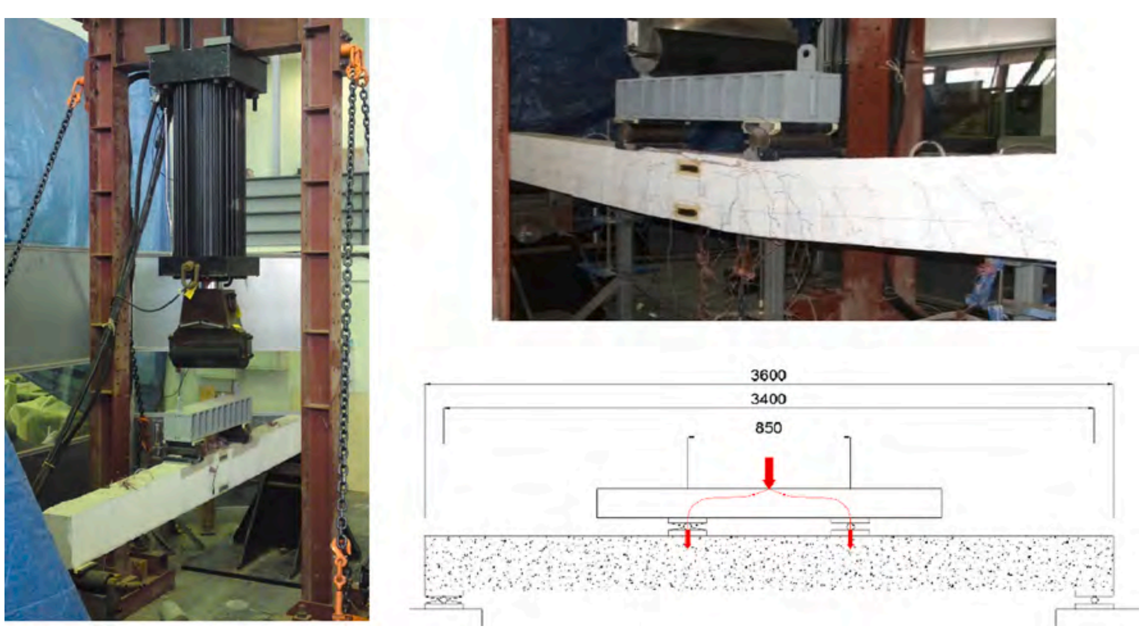


Fig. 4. Test setup of loading up to failure (short-term analysis and 3rd stage) [14].

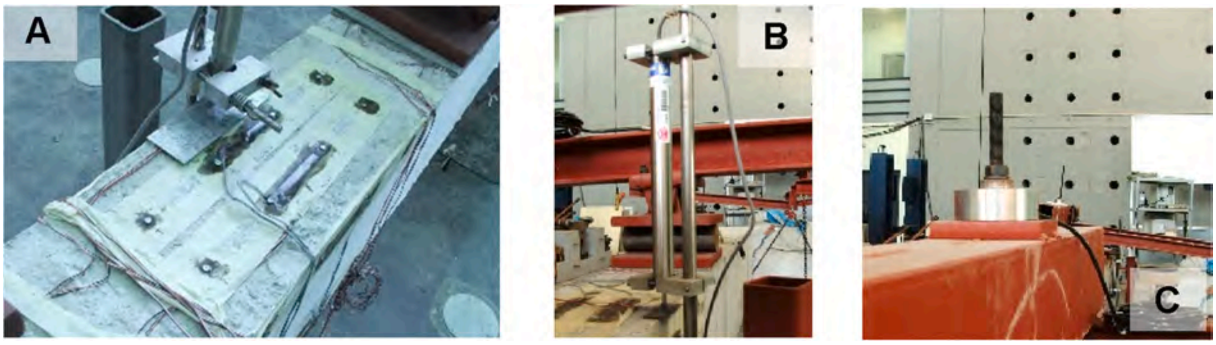


Fig. 5. Test instrumentation. A: Strain gauges on concrete beams. B: Displacement transducer. C: Load cell [14].

a loading cell and deflections and concrete strains were measured by concrete gauges and displacement transducers, respectively.

Fig. 6 summarises the different test stages performed and the test setup used for each one.

3.3. Concrete properties and test parameters

Mechanical properties of these concretes were obtained at different ages: 28 days, t_0 (loading age), t_1 (unloading age) and t_2 (test of pre-cracked beams) according to EN 12390–3 and EN 83316. Table 2 shows these mechanical properties.

The compressive strength and modulus of elasticity decrease as the replacement percentage of recycled aggregate increases. These reductions are about 30% when concretes with 100% of recycled aggregate are compared to baseline concrete for both properties. However, these differences lessen over time, being 21–27% at t_2. Regarding the modulus of elasticity, it can be seen that both conventional and recycled concretes at t_2 display similar values to those obtained at t_0. It is expected that these modulus of elasticity present slightly higher values due to the strength gain of concrete over time. However, it is worth noting that concrete specimens used to obtain the modulus of elasticity at t_2 were previously submitted to sustained load, unloaded and then, tested according to EN 83316, so the effect of concrete damage reduces this possible increment and leads to similar values at t_0 and t_2 [42].

4. Results and discussion

4.1. Concrete deformations: Strains and deflections

Some specific results and testing parameters have been listed in Table 3: stress value and level stress at the top side of the mid-span cross section of beam where the maximum stress value occurs, bending moment, cracking moment and deflection, instantaneous deformations (deflection at mid-span and concrete strain) at loading age (t_0), total deformations at t_1 and long-term deformations at this age, and deformations at t_2, after unloading and recovery period. Concrete deformations were measured at the span of the concrete beams, where maximum stress occurs. Regarding cracking moments, both experimental and theoretical one have been included in the table. They are significantly reduced as the content of recycled aggregate increases. This reduction is consistent with the lower tensile splitting strength, which leads to an earlier cracking of recycled concretes than with conventional ones [14].

Each concrete beam was subjected to different sustained loads due to its different compressive strength. As aforementioned, the loading value was calculated to obtain a maximum stress of 40% fc at the most compressed fibre of the concrete beam. Therefore, in order to compare results it is necessary to present strain curves over time taking into account the load applied. Fig. 7 shows the curves strain/stress – time during loading stage, unloading and recovery period.

As can be seen in Fig. 7, unitary strain (strain/stress) increases gradually with recycled aggregate content. This tendency is directly related to the lower modulus of elasticity of recycled concretes and confirms the higher deformability of these concretes. This effect is attributed to the adhered mortar of recycled aggregates that generates weaker ITZs leading to lower concrete strength and higher deformability of recycled concrete [14,33,43-45]. However, the unloading and recovery stage needs to be further analysed in order to determine the influence of recycled aggregates on concrete performance after removing the load. This analysis will be divided into two kinds of strain recovery:

- Recovery of instantaneous strain ($\varepsilon_{0,rec}$), defined as that obtained immediately after removing the load (immediate recovery of strain).
- Recovery of long-term strain ($\varepsilon_{LT,rec}$ (t)), which is obtained as the difference between the strain registered at age t and the recovery of instantaneous strain previously calculated.

Regarding deflections, curves of normalised deformations were calculated as the relationship between deflection and bending moment at midspan measured at different ages. As seen in Fig. 8, deflections are less influenced by the recycled aggregate content than concrete strains. This difference is attributed to the ductile design of the reinforcing steel which mainly withstands external loads in comparison to the concrete contribution. In addition, under serviceability conditions, concrete is usually cracked, so its contribution is limited in terms of a structural response such as deflection development over time. The differences between conventional and recycled concrete (on a material scale) are less when they are measured while analysing a concrete element.

Concrete with 20% recycled coarse aggregates displays a similar performance to that of conventional concrete in terms of deflections, while those with a high content of recycled aggregates (50 % and 100%) present slightly higher values of deflections, which are especially significant for H65 concretes. It can be stated that reinforced concrete with greater compressive strength (H50 series) is less influenced by the RCA content than H65 concretes in terms of deformability. This effect has been also detected in other properties such as concrete damage [42] or in the analysis of specific long-term deformations [13]. However, other studies [37-39,46] have revealed the opposite trend when basic properties such as compressive strength, tensile splitting strength, modulus of elasticity, bond strength or shrinkage are analysed, concluding that concrete with a low cement to water ratio (H50) leads to greater reductions in concrete properties.

To explain this phenomenon, it is necessary to analyse these results in detail. Firstly, it is worth noting that the load was applied as a percentage of compressive strength of each concrete to obtain a maximum stress level (σ/f_c) at the beam's midspan, i.e. lower than 0.4. Therefore, when deformations are normalised according to bending moment or stress, the effect of higher or lower strength or modulus of elasticity is removed. Regarding bond performance, it was found that normalised bond strength presents similar variations in concrete regardless of the

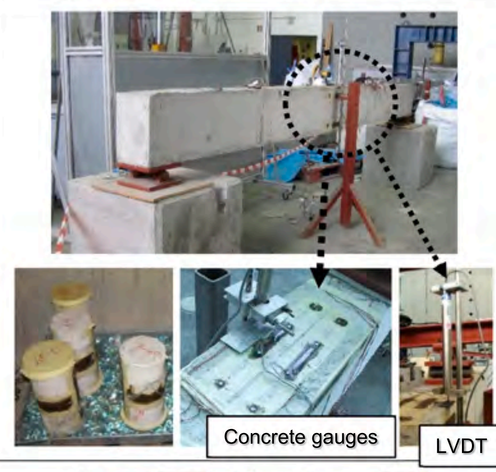
Short-term analysis	Flexural test up to failure of uncracked beams t=28 days	
Long-term analysis	**1st stage**: Flexural test under sustained load: - Loading age (t_0) = 42 days - Time of testing ($t-t_0$) = 1300 days	
	2nd stage: Unloading and measurement of recovery deformations: - Unloading age (t_1) = 1342 days - Time of testing ($t-t_1$) = 320 days	
	3rd stage: Loading up to failure of pre-cracked beams: - Loading age (t_2) = 1662 days	

Fig. 6. Test setup.

water to cement ratio when the replacement ratio of recycled aggregates changes [38]. At this stage, the factors governing the normalised deformations are others such as damage or time-dependent performance of concrete, which present a higher influence of the RCA content for concretes with greater compressive strength (H50 series) [13,42]. Lastly, the RCA content influences the cracking behaviour of recycled concrete with a high water to cement ratio (H65) to a greater extent than those with lower w/c ratios (H50). As a result, it can be concluded, according to these results, that reinforced concrete with lower compressive strength (H65) presents a higher influence of RCA content in terms of deformability than the H50 series, mainly due to the effect of cracking behaviour.

Table 2
Concrete properties.

Concrete H65		0%	20%	50%	100%
$f_{c,28}$	MPa	46,9	46,7	42,2	32,4
$f_{c,t0}$	MPa	50,3	47,2	41,6	32,3
$f_{c,t1}$	MPa	54,0	47,7	45,7	34,0
$f_{c,t2}$	MPa	54,2	49,3	49,2	41,6
$E_{c,28}$	MPa	35,200	32,500	27,400	24,100
$E_{c,t0}$	MPa	36,600	34,300	29,300	24,000
$E_{c,t2^*}$	MPa	36,500	34,500	31,900	26,400
Concrete H50		**0%**	**20%**	**50%**	**100%**
$f_{c,28}$	MPa	60,7	53,5	51,8	42,9
$f_{c,t0}$	MPa	65,7	59,1	53,1	45,3
$f_{c,t1}$	MPa	64,5	63,2	57,4	48,8
$f_{c,t2}$	MPa	64,2	62,82	59,5	50,5
$E_{c,28}$	MPa	36,300	32,900	31,600	25,900
$E_{c,t0}$	MPa	38,500	35,300	31,800	26,900
$E_{c,t2^*}$	MPa	38,800	35,500	32,000	27,000

*Values of modulus of elasticity at t_2 were obtained using the cylindrical specimens previously tested for creep analysis. These values cannot be compared directly to $E_{c,t0}$.

4.2. Recovery strains

Fig. 9 shows diagrams of bending moment –deformations at loading and unloading stages in terms of strains measured at the top of the mid-span of the concrete beams as shown in Fig. 5 (A). Instantaneous strain recovery is lower than that registered in the loading process. Differences between the loading and unloading branches enable the instantaneous plastic deformation to be defined, which is also known as irrecoverable instantaneous strain. As it is well-known, concrete displays a novel branch when load is applied for the first time. Subsequently, if the load is removed, deformation recovery will not present the same value, even for a linear range of concrete. The difference between both values (instantaneous deformation and instantaneous deformation recovery) will be the instantaneous plastic deformation of each concrete.

These diagrams reveal the higher deformability of recycled concrete during the loading process. At the unloading branch, recycled concretes with 20% of RCA display a similar slope to that of the conventional. However, for concretes with higher percentages of RCA some differences can be detected, especially for the H50 series. Comparing the loading and unloading branch, an increase of slope at unloading can be observed. As the concretes were loaded within the linear range, the modulus of elasticity could be calculated at t_0 and t_1 through the slope of the loading and unloading branch. These diagrams also enable the increase in concrete rigidity over time to be observed, due to the greater slope of the unloading branch compared to that of the loading. This is directly related to the concrete damage and modulus of elasticity that increases over time, leading to higher concrete rigidity. Therefore, in general, recycled concrete displays slightly higher deformations than conventional concrete, especially when a large content of recycled aggregates is used. As aforementioned, this effect is attributed to the adhered mortar that generates different interfacial transition zones (ITZs) that lead to higher deformability of recycled concrete.

In order to analyse the recoverability of recycled concretes, it is necessary to calculate the relationship between recovery strain over time and the strain developed under sustained load at t_1, before removing the load. The recoverability of concrete will be determined by the performance of the reinforcing steel and the concrete response after loading. Again, the ductile design of concrete structures leads to a

Table 3
Stress, moments, deflections and concrete strains at mid-span of RC beams.

		Concrete H65				Concrete H50			
		0%	20%	50%	100%	0%	20%	50%	100%
σ (stress)	MPa	14,19	13,43	10,34	9,80	21,92	16,14	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_{cr} (cracking moment predicted)	kNm	13,01	12,99	12,19	10,16	15,52	13,51	12,46	9,59
M_Q (loading 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 (instantaneous deflection at t_0)	mm	6,71	5,95	4.96	4,59	11,73	7,90	7,87	6,80
δ_{LT} (long-term deflection at t_1)	mm	4,87	5,86	4.67	6,75	6,66	5,97	6,21	8,40
δ (deflection at t_1)	mm	11,58	11,81	9,63	11,34	18,39	13,87	14,08	15,20
δ (deflection at t_2)	mm	4,38	6,29	5,35	6,04	7,68	7,47	7,01	8,54
ε_0 (instantaneous strain at t_0)	με	−433	−434	−327	−376	−442	−465	−472	−691
ε_{LT} (long-term strain at t_1)	με	−583	−708	−669	−753	−893	−755	−770	−810
ε (total strain at t_1)	με	−1016	−1142	−996	−1129	−1335	−1220	−1242	−1501
ε (total strain at t_2)	με	−637	−710	−627	−645	−779	−717	−591	−1046

*MQ: bending moment generated by the sustained load applied for long-term tests.

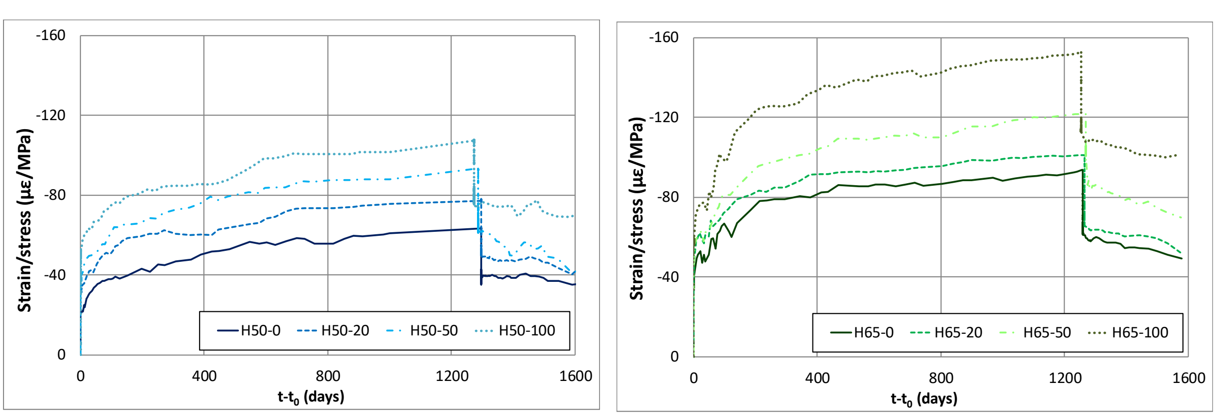


Fig. 7. Curves strain/stress – time during loading stage, unloading and recovery period.

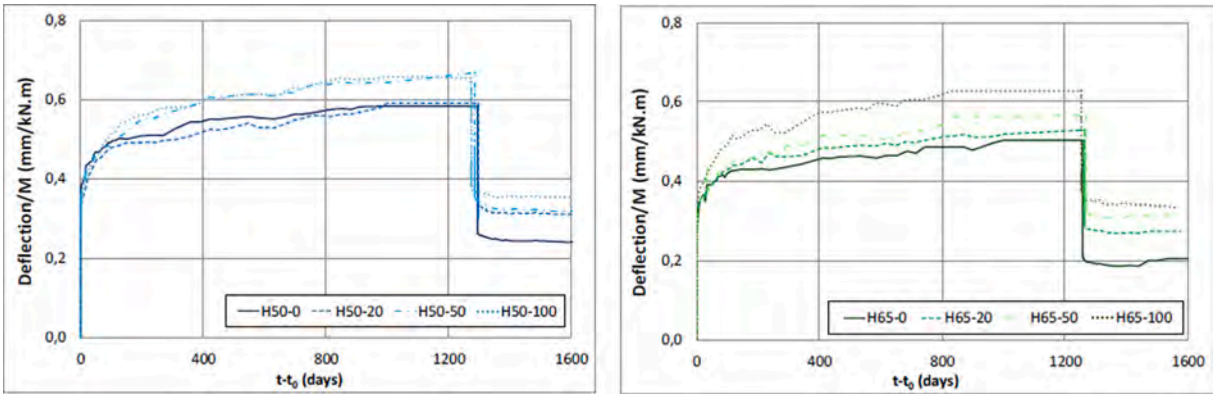


Fig. 8. Curves deflection/M – time during loading stage, unloading and recovery period.

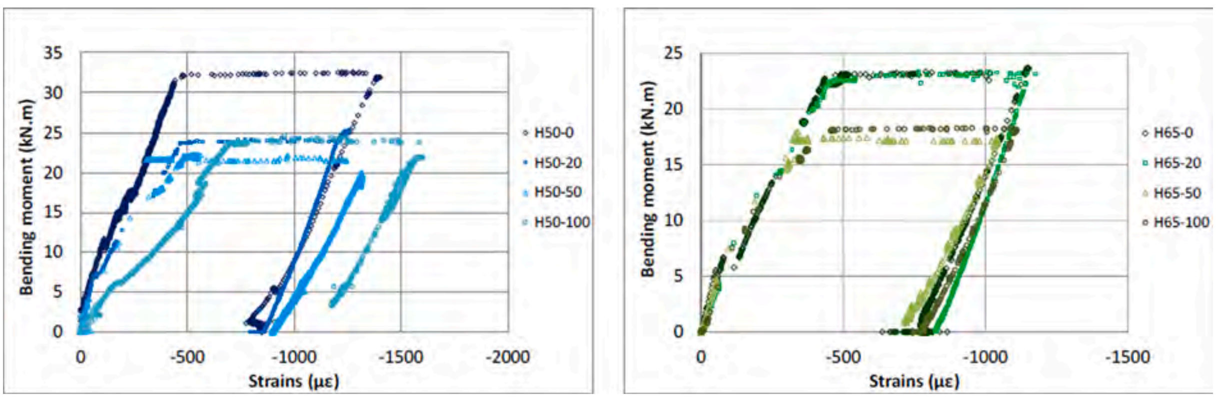


Fig. 9. Diagrams bending moment –strains at loading and unloading stages.

limited influence of concrete, even after periods of loading and unloading of concrete under compression. They all show a recoverability of around 40%. Fig. 10 shows these curves and as the amount of longitudinal reinforcement was the same for all beams it is seen that recycled concrete displays only slightly lower strain recoverability compared to the conventional for the H50 series. In addition, no significant differences have been found for H65 concretes. Considering that strain recoverability is directly related to concrete damage it can be stated that recycled concretes with higher strength (H50) show lower proportions of recoverable deformations due to the higher influence of the RCA content in terms of damage in H50 recycled concretes compared to those in H65 series. These results are consistent with the conclusions obtained by Mei et al. [21], who found that concretes with higher strength show lower proportions of recoverable creep. It is assumed that the long-term strain of all of these concrete specimens (concrete age of more than 3 years) are mainly due to the effect of creep.

4.3. Deflection recovery

Concrete deflections were also measured at the loading and unloading stages over time. This analysis is divided into two different parameters, the instantaneous deflection recovery after removing the load and the long-term deflection recovery, registered over 320 days after removing the load. Fig. 11 shows the diagrams bending moment – deflection during loading and unloading and reveals the higher deformability of recycled concrete during the loading process.

In order to analyse the recoverability of recycled concretes, it is necessary to calculate the relationship between deformation recovery

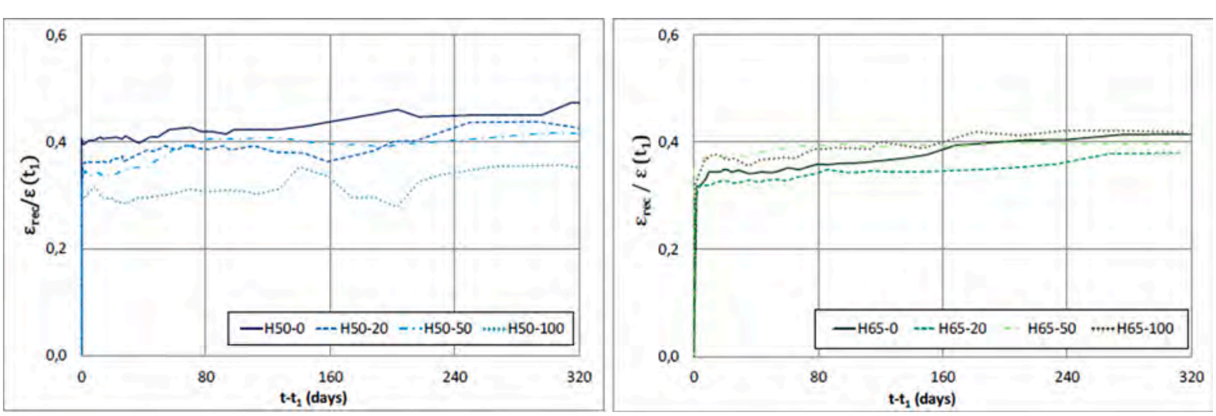


Fig. 10. Recoverability of strains over time.

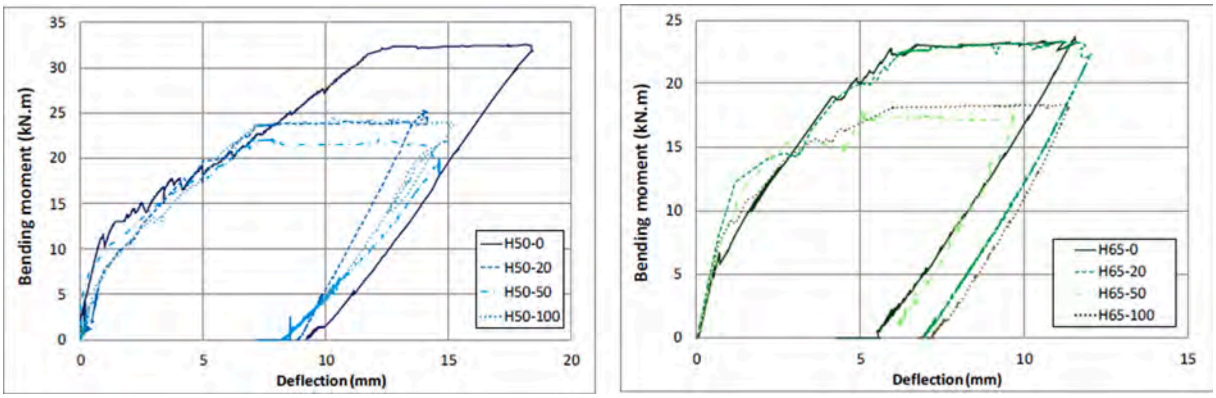


Fig. 11. Diagrams bending moment –deflections at loading and unloading stages.

and deformation due to the applied load. This parameter reveals that both recycled and conventional concrete show a recoverability of instantaneous deflections from 70 % to 80 % for the H50 series and from 80 % to 90 % for H65. It can be noted that no significant differences have been detected between recycled and conventional concrete in terms of instantaneous deflection recovery. As previously discovered [14,47], deflections in concrete structures under serviceability conditions cannot be directly related to material properties by considering only the modulus of elasticity, especially when high amounts of reinforcement steel are used due to the ductile design of the structures. This kind of design (widely used for concrete structures in real applications) leads to very slight increments in deflection at serviceability, despite the lower modulus of elasticity of recycled concrete, both in the loading and unloading processes.

In order to analyse the influence of recycled aggregate on the recoverability of concrete in terms of instantaneous deflections, it is important to determine all properties and parameters affecting this recoverability. As it is well-known, instantaneous deflections are directly related to the load applied and the section rigidity, which depends on modulus of elasticity and moment of inertia. As aforementioned, the value of the load was calculated according to concrete strength, so instantaneous deflections are different for each concrete depending on this value and are in accordance with concrete performance, mechanical strength and modulus of elasticity. However, there are other conditioning factors and parameters such as concrete cover, moment of inertia and amount of reinforcement steel. In this regard, it is worth noting that recycled concrete beams have the same reinforcement steel and concrete cover as those of conventional concrete, so these factors are not considered. Therefore, the only factor that can lead to differences in terms of instantaneous deflection recovery is the moment of inertia. In order to determine how this parameter varies as the content of recycled aggregate increases, all affecting factors are identified and analysed. When concrete structures are cracked, as usual under serviceability conditions, the moment of inertia is defined as the effective moment of inertia (I_{eff}) and is calculated according to Bransońs equation (Eq. (1)) taking into account the cracking moment (M_{cr}), bending moment due to load applied (M_a), gross moment of inertia (I_g) using the dimensions of concrete section, and the cracked moment of inertia (I_{cr}).

$$I_{eff} = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \leq I_g \tag{1}$$

This expression is adopted by different structural codes to obtain the effective moment of inertia such as in ACI 318 and Spanish Structural Code (EHE-08) [40,48].

The cracking moment of inertia depends on the relationship between the modulus of elasticity of steel and concrete ($\alpha = E_s/E_c$), the depth of the compression zone (x) and the amount and position of reinforcement steel. Therefore, it is important to know if the depth of the compression zone undergoes any significant changes when recycled aggregates are used. As noted in a previous study on the short-term flexural behaviour of reinforced concrete beams made with recycled coarse aggregates [14], the depth of the compression zone hardly shows any differences between conventional and recycled concretes. Only concrete with 100% recycled aggregate displays slight increments in this value in accordance with the results obtained by Choi et al. [35]. This difference is associated with the lower flexural stiffness of recycled concrete, and consequently, greater deformations that lead to an increment in the compression zone, which is especially noticeable for high replacement percentages (100%).

Based on these assumptions, and considering that recovery deflection grows to the same extent as deflection under load, it can be noted that the content of recycled coarse aggregate has a slight influence on deflections under serviceability conditions, and consequently, on the recovery of instantaneous deflections. Therefore, the recoverability of recycled concrete is similar to that of the conventional in terms of instantaneous deflections.

However, Choi et al. [35] found that recycled concrete beams show higher recovery values for instantaneous deflections. This different trend is probably related to dissimilarities between both studies in terms of the properties of the recycled concrete and recycled aggregates. On one hand, they used recycled fine and coarse aggregates with a lower water absorption capacity (1.84% for recycled coarse aggregates and 3.64% for recycled fine aggregates) which makes these recycled aggregates similar to the conventional. On the other hand, the recycled concrete presents higher mechanical strengths and modulus of elasticity than the baseline concrete, probably due to the concrete mixing design and procedure. Therefore, it is difficult to establish straightforward comparisons between their results and those obtained in this research. Indeed, further research is required in this regard.

Fig. 12 shows the recoverability of concrete deflections over time after removing the load. Similar to strain analysis, these curves were obtained as the relationship between the recovery deflection at $t\text{-}t_1$ and the deflection at t_1 (before unloading). These results reveal the significant influence of recycled aggregate content on concrete performance. Conventional concrete recovers around 60% of its deflection at 320 days after removing the load, while recycled concrete shows slightly lower percentages of deflection recovery, between 45% and 55%. This effect is attributed to the different time-dependent properties of recycled concrete (creep and shrinkage), concrete damage and cracking behaviour [13,14,42,46]. The influence of these properties are more thoroughly discussed later when long-term deflection recovery is analysed.

It has been also noted that deflection recovery occurs mainly over the first few days. This trend is consistent with the loading stage, where most deformations occur during the first few days after loading [49].

Once instantaneous deflection recovery occurs after removing the load, the concrete continues recovering deformations over time and this is known as long-term deformation recovery. Considering that the

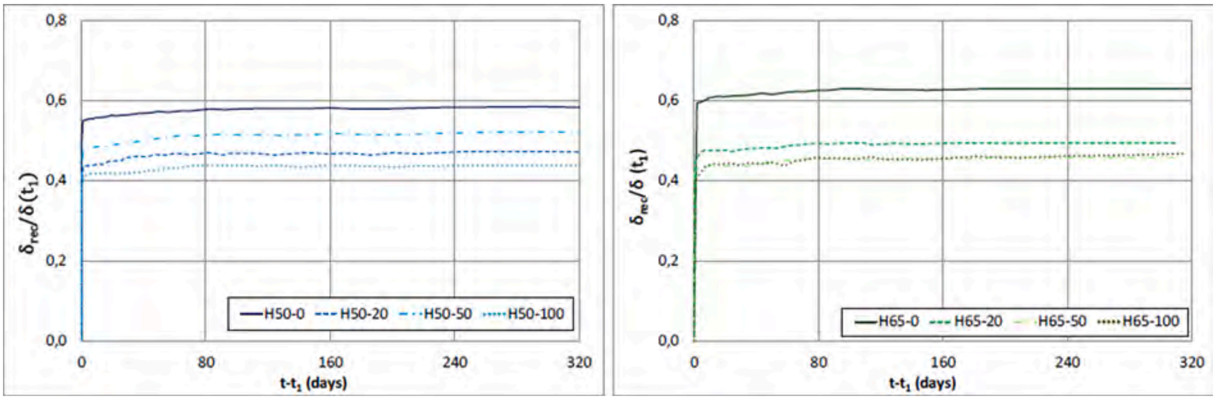


Fig.12. Recoverability of deflections over time.

instantaneous deflection recovery of recycled concretes presents similar values to that of conventional concretes, differences in terms of deflection recovery are attributed to long-term deflection recovery. Many authors [31,39,43,45,50] have found that recycled concrete undergoes greater long-term deformations due to creep and shrinkage than the conventional, which results in greater long-term deflections [13]. It was expected that greater long-term deflections of recycled concrete under sustained load would lead to greater long-term deflection recovery after removing the load, and consequently, similar recoverability is observed in both recycled and conventional concrete. However, as can be seen in Fig. 13, conventional concrete recovers between 23% (H50-0) and 26% (H65) of its long-term deflection, while recycled concretes present lower recovery percentages (22% for H50-20, 18% for H50-50, 11% for H50-100, 20% for H65-20 and 17% for H65-50 and H65-100). These differences are attributed to the greater cracking and damage of recycled concrete [14,42], which results in a lesser ability to recover long-term deflections and therefore, greater permanent deflections. Again, concretes with higher strength show lower proportions of recoverable deformations [21].

A concrete structure usually withstands different loading stages during its service life and consequently, the values of permanent deformations must be considered in structural analysis. The different performance of recycled concrete in this regard has to be taken into account in structural design, especially for structural applications of concrete with a high content of recycled aggregates.

4.4. Analysis of uncracked and cracked concrete beams

Once the long-term behaviour has been analysed, this section focuses on comparing results from flexural tests up to failure of reinforced concrete beams both uncracked (at 28 days of concrete age) and pre-cracked after a period of sustained load and recovery (at 1662 days of concrete age). As can be seen in Fig. 14, yielding and ultimate bending moments of cracked beams are similar to those obtained for uncracked ones. This is attributed to the steel contribution, which does not present any detrimental effects due to the previous period of loading (load under the 40% of concrete fc). As expected, the main difference between pre-cracked and cracked reinforced concrete beams is the loading branch. These two diagrams, especially in the first part of the loading branch up to 30 kN.m (around 50% of ultimate bending moment), enable the tension-stiffening of concrete to be analysed.

As it is well-known, concrete structures are usually loaded under the cracking stage during their service life. When concrete is loaded above the cracking load, it presents a behaviour somewhere between uncracked and fully cracked performance requiring a non-linear sectional analysis [30]. As a result, effective flexural stiffness is calculated by the Bransońs equation (Eq. (1)) or other methods such as those collected in Eurocode [29] or Model Code [30]. In the cracking performance, it is possible to identify the tension-stiffening which is known as the contribution of concrete to withstand external loads once the concrete is cracked and it is related to bond performance (stress transfer), the cracking behaviour of concrete and the stress–strain relationship.

These experimental results reveal that recycled concrete presents lower tension-stiffening than the conventional, especially for high replacement ratio percentages. This effect is attributed to the bond performance of recycled concrete being worse than that of the conventional [5,38,51], and its premature cracking and higher crack width [14], which is also related to bond behaviour. Cracking moments decrease as the content of recycled aggregate increases in accordance with reductions in tensile splitting strength [14]. All of these factors lead to the lower effective flexural stiffness of recycled concrete when compared to the conventional.

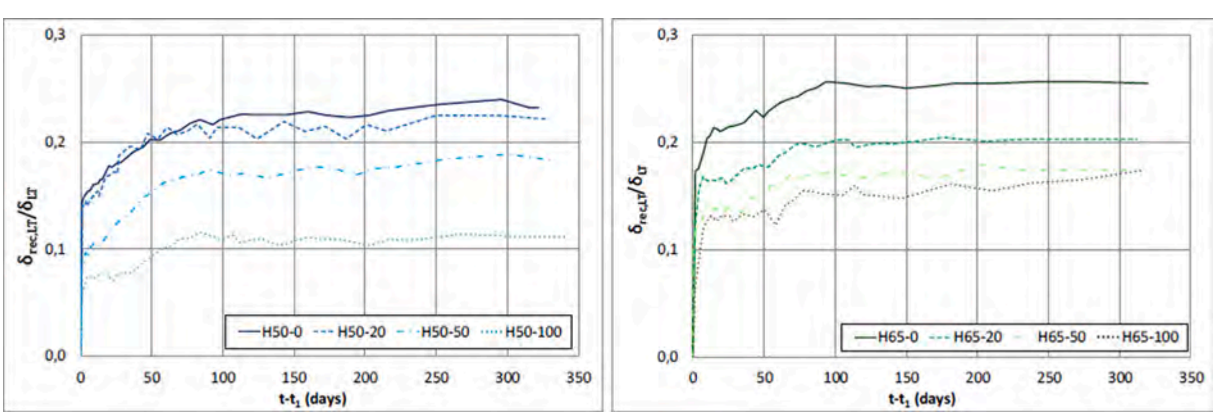


Fig.13. Recoverability of long-term deflections over time.

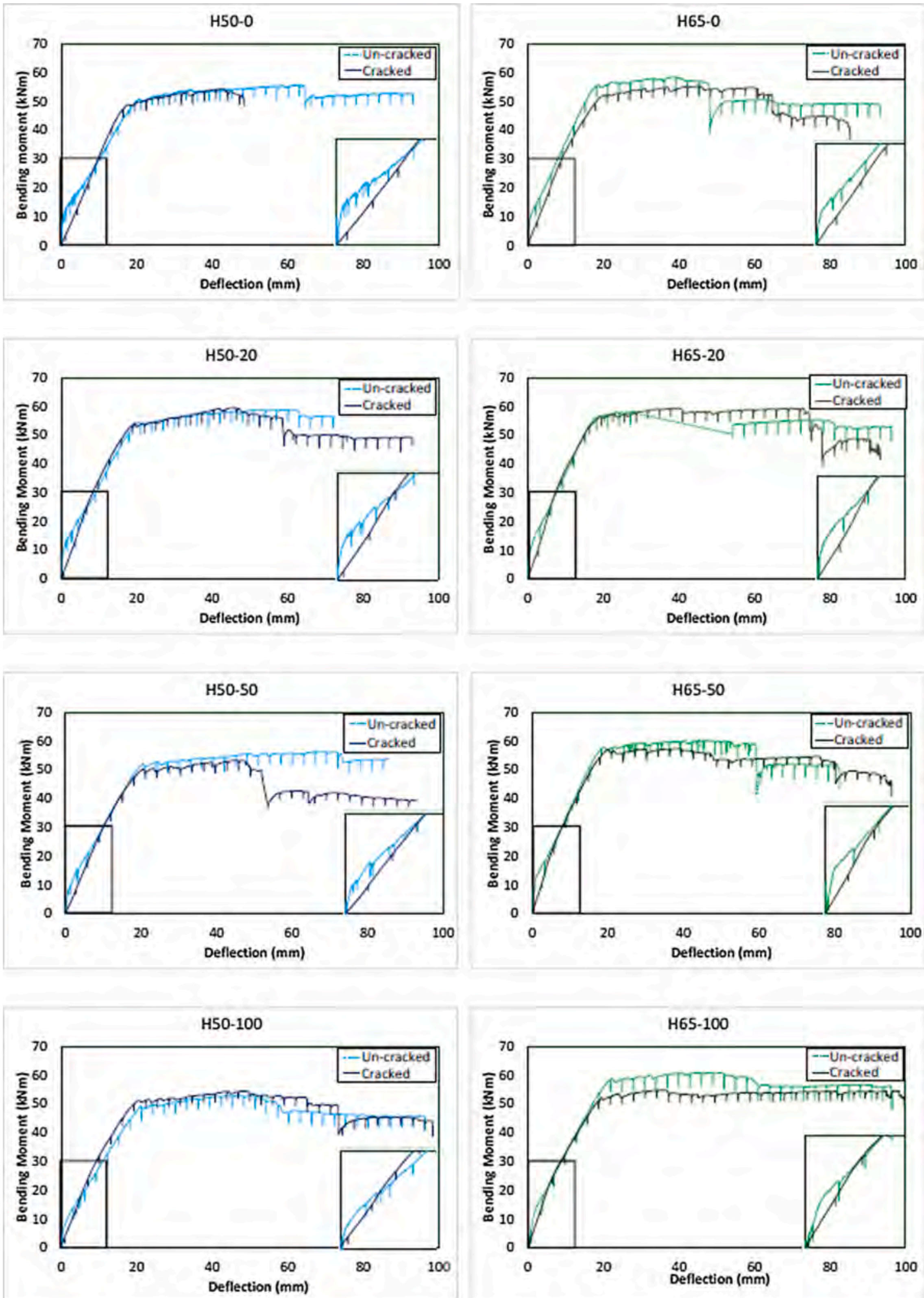


Fig.14. Diagrams bending moment – deflection of uncracked and pre-cracked beams.

As a conclusion, it can be stated that once cracking occurs, the lower bond strength of recycled concrete leads to greater crack widths and lower concrete contribution, which results in lower tension stiffening. Finally, at the yielding and ultimate stage, no significant differences have been detected in terms of concrete performance due to the ductile design of reinforcement steel that results in limited concrete contribution at failure.

5. Conclusions

In this work, the recovery performance of recycled aggregate concretes has been determined and cracked and uncracked concrete beams were analysed. Based on these results the following conclusions can be drawn:

- The unitary strains (strain/stress) increase gradually with the recycled aggregate content, although deflections present a lower influence of recycled aggregate content than concrete strains. This is attributed to the ductile design of reinforcing steel that leads to a limited concrete contribution in terms of structural response under serviceability conditions.
- Therefore, in general, recycled concrete displays slightly higher deformations than conventional concrete, especially when a large content of recycled aggregates is used both during the loading and unloading processes. In terms of recovery strains, some differences have been detected in recycled concrete with high percentages of RCA (50% and 100%). When comparing the loading and unloading branch, an increment in concrete rigidity over time has been observed.
- The recoverability of concrete is determined by the performance of the reinforcing steel and the concrete response after loading. All concretes show a recoverability of around 40%. However, some differences have been detected between the H50 series and H65 series. While H65 concretes do not present significant differences, recycled concrete of the H50 series presents slightly lower strain recoverability than the conventional.
- Recycled aggregate content influences concrete performance in terms of deflection recovery over time. While conventional concrete recovers 60% of its deflection, recycled concrete shows slightly lower percentages of deflection recovery. Taking into account that recoverability of instantaneous deflections of recycled concretes presents similar values to those obtained for conventional concrete, this difference is attributed to recovery of long-term deflections. The greater cracking and damage of recycled concrete result in a lesser ability to recover long-term deflections (23% − 26% for conventional concrete and 11% − 22% for recycled ones). It can be concluded that recycled concrete presents greater permanent deflections than conventional concrete.
- Regarding the analysis of cracked and uncracked concrete beams, it can be noted that cracking moments decrease as the content of recycled aggregate increases, in accordance with reductions in tensile splitting strength. In addition, once cracking occurs, the lower bond strength of recycled concrete leads to greater crack widths and lower concrete contribution, which results in lower tension stiffening and consequently low effective flexural stiffness, especially for high replacement ratio percentages. Finally, at the yielding and ultimate stage, no significant differences have been detected in terms of concrete performance.

A concrete structure usually withstands different loading stages during its service life and consequently, the values of permanent deformations must be considered in structural analysis. The different performance of recycled concrete in this regard has to be taken into account in structural design, especially for structural applications of concrete with a high content of recycled aggregates.

CRediT authorship contribution statement

Sindy Seara-Paz: Formal analysis, Investigation, Writing – original draft. **Belén González-Fonteboa:** Formal analysis, Writing – review & editing, Supervision. **Fernando Martínez-Abella:** Writing – review & editing, Supervision. **Javier Eiras-López:** Writing – review & editing.

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.

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