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Effect of fine and coarse recycled concrete aggregate on the mechanical behavior of precast reinforced beams: comparison of FE simulations, theoretical, and experimental results on real scale beams

Mirian Velay-Lizancos*[1], Pablo Vazquez-Burgo[2], David Restrepo[3], Isabel Martinez-Lage[2]

[1] Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA.

[2] Grupo de Construcción, Centro de Innovación Tecnológica en Edificación e Ingeniería Civil (CITEEC), E.T.S. Ingenieros de Caminos, Canales y Puertos. Universidade da Coruña, Campus de Elviña, s/n, 15071 A Coruña, Spain

[3] Department of mechanical engineering, The University of Texas at San Antonio. TX 78249, USA

*Corresponding author, E-mail address: mvelayli@purdue.edu. Phone number: +1 (765) 496-8301.

16-digit ORCID: 0000-0002-1539-7923

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ABSTRACT

In this work, we present the effect of using coarse and fine recycled aggregate jointly as a partial replacement of natural aggregate in self-compacting concrete in the mechanical performance of precast beams. The replacement levels of recycled aggregate were set to 0%, 20%, 35%, and 50% of the total amount of aggregate. The effect of the partial replacement of coarse and fine recycled aggregate jointly in the mechanical and physical properties of concrete was analyzed at 28 days. Then, a total of 8 reinforced beams were cast (two beams per each concrete studied) to determinate the effect of the partial replacement of recycled aggregate. One of the beams of each concrete was designed and tested to determine the flexural strength, and the other beam was used to determine the shear strength. The flexural and shear strengths obtained from the tests of real-scale beams were compared with theoretical analyses based on standards EC-2 and EHE-08, and by computational analyses based on the finite element method (FEM). These comparison, allowed us to assess the use of theoretical and computational models as tools to predict the mechanical behavior of real scale beams under different loading conditions (flexural and shear tests) when different proportions of recycled aggregate are used. According to the results, for the shear test, the theoretical models based on standards can be applied for concrete structures regardless of the percentage of recycled aggregate, without losing accuracy in comparison with beams made of plain concrete. In contrast, under flexural conditions, the theoretical models based on the standards are only applicable when considering 20% or less recycled aggregate. In general, computational models based on FEM show good agreement with experimental results in all the studied cases.

KEY WORDS: *Sustainable construction; Coarse recycled aggregate; Fine recycled aggregate; Mechanical properties; Structural concrete; eco-concrete; FEM*

Highlights:

Fine recycled aggregate is not allowed to make structural concrete

Full scale beams with different percentages of recycled aggregate were made

Fine and coarse recycled aggregate were used jointly

The studied percentages were 0%, 20%, 35% and 50% of the total aggregate

Accuracy of theoretical and FEM were tested in function of the replacement

1. Introduction

Waste management is currently required to prevent negative environmental impacts around the world [1], [2]. The management of all types of waste is considered to be significant, in particular, waste produced in precast concrete plants, which is the subject of this research study. In general, the use of recycled aggregate in structural concrete is not allowed or is very limited in different standards. For instance, the Spanish code EHE-08 [3] limits the use of coarse recycled concrete aggregate in new structural concrete production up to 20% by weight of the total coarse aggregate content (as long as this aggregate complies with a series of geometric, physical, and chemical requirements). Moreover, many other standards around the world (e.g. United Kingdom, Portugal, Germany, Brazil, Spain) do not allow the use of fine recycled aggregate in structural concrete [4].

Precast concrete typically exhibits a characteristic concrete strength above 40 MPa. Therefore, the crushing of concrete waste and later removal of contaminants allows obtaining high quality recycled aggregates. However, after concrete crushing, approximately 40%-50% of the material has a particle size less than 4 mm (corresponding to fine aggregate typical size), and therefore, it cannot be used to produce new concrete according to the current standards around the world [4]. In consequence, almost half of this waste material cannot be recycled, making waste management economically unfeasible. An alternative solution to this problem is the use all of the aggregates resulting from the recycling process (fine and coarse recycled concrete aggregates, jointly without sieving) as a partial replacement of natural aggregates to make new structural concrete. However, given the current restrictions provided by different standards, research about the effects of fine and coarse recycled aggregate used jointly in structural concrete is necessary to evaluate the effects on mechanical performance and enable its feasibility on the fabrication of structural elements.

The influence of the coarse recycled aggregate on the mechanical properties of concrete has been widely studied [5]–[15]. The feasibility of fabricating recycled concrete using fine recycled aggregate produced from the crushing of concrete is an active research topic. Previous studies [9], [16]–[25] have shown that increasing the substitution percentage of fine or coarse natural aggregate by recycled aggregate reduces the compressive strength, the splitting tensile strength, and the elastic modulus of concretes to varying extents. However, Evangelista et al. [26] obtained similar compressive strength for a reference concrete and for a concrete with 100% replacement of fine aggregate. Pedro et al. [27] noticed a decrease in the mechanical properties concerning durability, creep and shrinkage of concretes with recycled concrete aggregate, both fine and coarse, in comparison with concretes without recycled aggregate. But the values reached are adequate to use these aggregates in most of the structural elements.

The flexural and shear behaviour of full-scale reinforced beams with coarse recycled concrete aggregate has also been studied for several authors [11], [12], [28]–[35]. There is also a study of the flexural behaviour of reinforced concrete beams made with fine recycled concrete aggregates (but no coarse recycled aggregate) [36]. There are a few studies of the influence of fine and coarse recycled aggregate on the flexural or shear behaviour of reinforced beams, [37]–[42]. Most of them conclude that recycled concrete aggregate beams show very promising results in terms of flexural strength. Ajdukiewicz and Kliszczewicz [40], [41], observed similar bearing capacity of the studied members (beams and columns) with and without recycled aggregate, but significantly greater deformations of concrete in members with recycled aggregate. With regard to the shear behaviour, they drew the conclusion that the shear strength was lower as the replacement level increased, even when the recycled aggregate is only coarse.

The application of finite element methods (FEM) for the evaluation of flexural and shear behaviour of concrete elements has been performed for several authors [43]–[45]. For instance, in a recent study, Sun [43] performed a three-dimensional FEM model of push-off tests for recycled aggregate concrete elements. The study presents a simulation of the shear transfer behaviour of the push-off specimens and analyses the effect of different parameters across the shear plane. Based on the FEM results and parameter studies, the following conclusions were drawn: The FEM model was consistent with the experimental results; for recycled aggregate concrete (RAC) beams with the same concrete strength, the ultimate shear strength increases when the lateral reinforcement ratio rises, but the stirrup diameter has not significant influence; and the ultimate shear strength decreased 13.8% when the replacement ratio of coarse natural aggregate by coarse recycled aggregate rose from 0% to 100%.

Studies comparing the accuracy of FEM and theoretical estimations with the results of full-scale experimental tests of concrete beams in function of the percentage of fine and coarse recycled aggregate used jointly, have not been found.

This research aims to contribute to the progress of the standards towards a more eco-friendly regulations, without compromising the safety. The main objective of this research is to evaluate the influence of fine and coarse recycled aggregate on the accuracy of theoretical and FEM models to predict the behaviour of real scale beams under different solicitations (flexural and shear tests). To achieve this, we fabricated reinforced beams made of self-compacting concrete with fine and coarse recycled aggregate from the same precast facility. Concrete reinforced beams with replacement levels of 0, 20, 35 and 50% of the total amount of aggregate were considered in this study.

2. Materials

2.1. Concrete components

The following materials were used in this study.

- Cement CEM-I 52.5 N/SR
- Limestone filler
- Natural quartzite sand: 0/2.5 fraction (NA 0/2.5) and 0/5 mm (NA 0/5)
- Natural granite gravel: 6/12 fraction (NA 6/12)
- Recycled concrete aggregate: 0/12 fraction (RA 0/12). These aggregates were obtained by crushing the existing waste from a precast concrete plant. The materials were taken to a construction and demolition waste plant for recycling, where they were treated by crushing, removing impurities and sieving. This recycled aggregate has a 47% of fine recycled aggregate and a 53% of coarse recycled aggregate. It is the same recycled aggregates used in other two studies published [46], [47].
- Visocrete 20 HE superplasticiser.

Table 1 shows the chemical analysis results from X-ray fluorescence for all of the components that were used in this study. The compounds of the recycled aggregate were classified following the standard EN 933-11 [48]. The results show that almost all (> 99%) of the particles could be classified as R_c "Concrete, concrete products, mortar" (93%) or R_u "Unbound aggregate, natural stone" (6.7%), as expected. No clay, bituminous materials or glass was found.

Table 1. Chemical composition (wt. %)

Component	Cement	Filler	NA 0/2.5	NA 0/5	NA 6/12	RA 0/12
CaO	65.5	55.4	0.031	0.031	1.2	16.0
SiO_2	18.6	1.3	97.5	97.5	67.8	53,2
Fe_2O_3	4.7	0.25	0.40	0.40	2.3	2.1
SO_3	3.6	0.11	-	-	0.03	0.74
Al_2O_3	3.0	0.53	1.2	1.2	15.9	8.3
MgO	0.79	0.58	-	-	0.70	0.82
K_2O	0.65	0.11	0.14	0.14	6.0	3.1
Na_2O	0.45	-	-	-	3.8	1.2
CO_2	-	41.6	-	-	-	-
LOI	1.7	-	0.31	0.31	1.3	13.4

Table 2 shows the percentage of material passing through 0.063-mm and 4-mm sieves (these values are limited in many regulations) and the densities and water absorption values that were obtained according to EN 1097-6 Standard [49].

Table 2. Particle size distribution, particle density and water absorption

Property	NA 0/2.5	NA 0/5	NA 6/12	RA 0/12
% passing 0.063 mm (%)	1.94	1.49	0.43	3.61
% passing 4 mm (%)	100	100	3.72	40.64
Apparent particle density (Mg/m^3)	2.79	2.90	2.62	2.55
Oven-dried particle density (Mg/m^3)	2.74	2.88	2.55	2.21
Saturated surface-dried particle density (Mg/m^3)	2.76	2.88	2.58	2.34
Water absorption (%)	0.67	0.30	1.04	6.06
Sieve size (mm)	**Percentage passing (by weight) (%)**			
0.063	1.9	1.5	0.4	3.6
0.125	3	5	1	6
0.25	10	17	1	9
0.5	33	41	1	13
1	62	63	2	17
2	90	80	3	24
2.5	96	84	-	-
4	100	92	4	41
5	100	96	5	53
5.6	100	98	6	56
6.3	100	100	12	68
8	100	100	35	84
10	100	100	86	98
11.2	100	100	99	100
12.5	100	100	100	100
14	100	100	100	100
16	100	100	100	100
20	100	100	100	100
25	100	100	100	100
31.5	100	100	100	100
63	100	100	100	100

Finally, for the recycled aggregate, the value of the flakiness index according to EN 933-3 [45] is 5 and the Los Angeles abrasion coefficient according to EN 1097-2 [50] is 38, lower than the values permitted by EHE-08 [3].

2.2. Concretes mixtures

Four different mixtures of concrete are used in this study. All the concretes are self-compacting concretes. The reference concrete was named M-0, and it does not have recycled aggregate. The other concretes have replacement levels of 20%, 35%, and 50%; named M-20, M-35 and M-50 respectively. Note that the percentage of replacement was calculated with respect to the total amount of aggregate (fine and coarse), therefore, the amount of natural aggregate replaced is significant even in low percentages. For example, M-20 has a total of 47% of fine natural aggregate (NA 0/5) and 53% of coarse natural aggregate (NA 6/12) replaced by fine and coarse recycled aggregate respectively (RA 0/12). The fractions were not separated by sieving in order to do the process more sustainable (energetic saving) from the environmental and economic point of view. Table 3 shows the concrete mixes that were used in this study.

Table 3. Mix design

Component	M-0	M-20	M-35	M-50
Cement (kg)	335	335	335	335
Filler (kg)	320	320	320	320
NA 0/2.5 (kg)	370	370	370	370
NA 0/5 (kg)	510	375	273	172
NA 6/12 (kg)	810	607	455	303
RA 0/12 (kg)	---	338	592	845
Superplasticizer (kg)	5.4	5.4	6	6
Effective water/cement ratio	0.5	0.5	0.5	0.5
Volume (m^3)	1.000	1.009	1.015	1.022

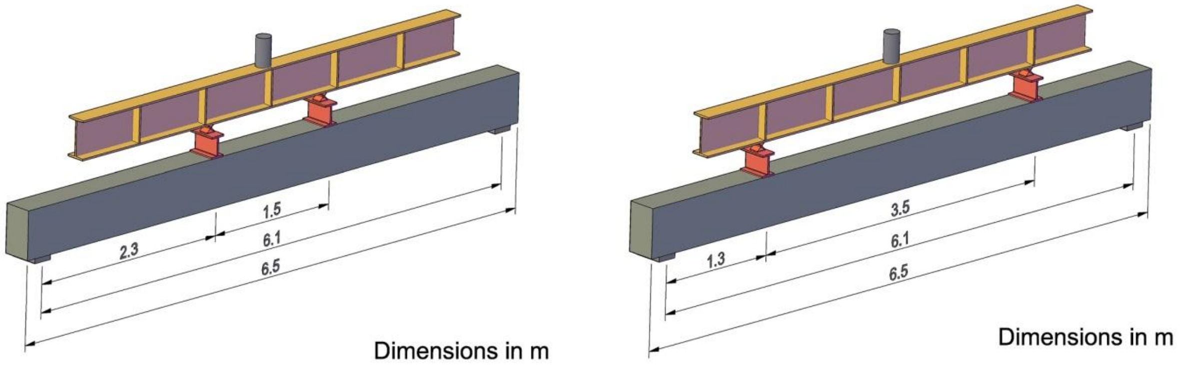
Before the mixing, the aggregates were close to the saturated surface dry condition. The moisture content of each aggregate was determined. Following previous studies [34], [51], [52], we assumed that the aggregates absorb 100% of their absorption capacity. We adjusted the mixing water accordingly to achieve the target water/cement ratio.

3. Methods

3.1. Real scale tests of beams

A total of 8 beams were fabricated and tested. Each beam had a total length of 6.50 m and a span length of 6.10 m. The loading was applied by two symmetrical concentrated loads as shown in Figures 1 and 2. Two beams were tested for each substitution percentage: one beam was aimed to flexural failure with 1.50 m load spacing (Fig. 2a), and the other beam was aimed to shear failure with 3.50 m spacing (Fig. 2b).

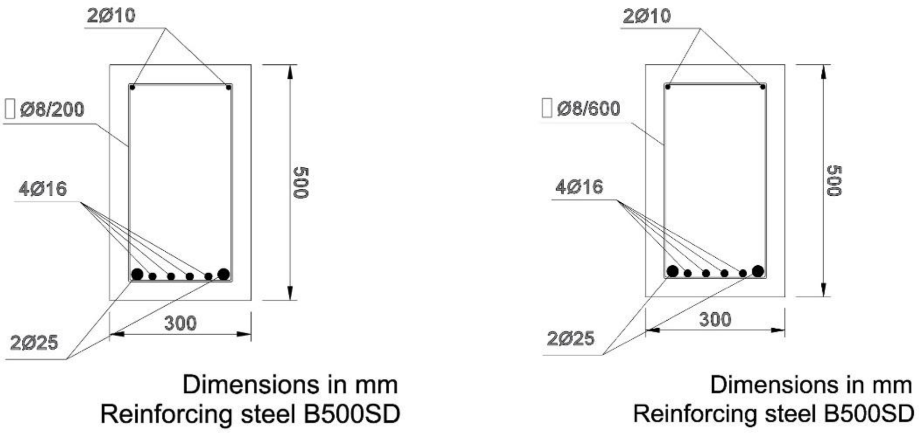
Figure 1. Beam of 6.5 m of length



a) Flexural test b) Shear test

Figure 2. Schematic test set-up

The cross section for flexural test beams and shear test beams is depicted in Fig. 3a and Fig 3b respectively. The tests were performed in 2 ton (19.62 kN) increments, and the deflection at mid-span was measured for each test. In addition, cylindrical samples of 150 mm x 300 mm were cast for all of the mixes and were tested for compressive strength and elastic modulus at 28 days, and the density of the each concrete mix was measured.



a) Flexural test b) Shear test

Figure 3. Cross section of the beam

3.2. Theoretical methods.

To calculate the theoretical flexural moments, the following hypothesis has been considered based on the Eurocode EC-2 and the “Spanish standard of structural concrete” (EHE-08).

For concrete, the stress-strain diagram used was the parabola-rectangle diagram, the unit stress under maximum load is 2‰ and the ultimate unit stress 3.5‰. The tensile strength was neglected.

For steel, the assumed stress-strain diagram was the typical double-line diagram. The steel maximum strain (tensile) 1% (it means 10 ‰). Its yield strength assumed is 500 MPa, the ultimate unit load is 550 MPa and the elastic modulus 200.000 MPa.

The calculation of the theoretical shear forces has been performed following the prescriptions of the EC-2 and the EHE-08 (they are the same). The ultimate shear force is calculated considering both, the concrete contribution and the shear reinforcement contribution. The ultimate force due to the web compression fatigue (V_{u1}) and the ultimate force in the tensile web fatigue need to be verified. The latter is equal to the sum of the concrete contribution and the steel contribution ($V_{u2}=V_{cu}+V_{su}$).

For rectangular sections and vertical cross reinforcement without axial force, these values have been calculated with Eq.1, Eq. 2 and Eq. 3.

$$V_{u1} = 0.30 \cdot f_{cd} \cdot b \cdot d \tag{1}$$

$$V_{cu} = \frac{0.15}{\gamma_c} \xi (100 \cdot \rho_1 \cdot f_{ck})^{1/3} \cdot b \cdot d \tag{2}$$

$$V_{su} = A_{90} \cdot f_{y90,d} \cdot 0.90 \cdot d \tag{3}$$

Where:

V_{u1}: ultimate force due to the web compression fatigue.

V_{u2}: ultimate force in the tensile web fatigue.

V_{su}: Contribution of the vertical cross reinforcement to the shear force strength.

V_{cu}: Contribution of concrete to the shear force strength.

f_{cd}: Concrete compressive strength.

b: concrete section width.

d: concrete effective depth with regard to the flexural longitudinal reinforcement.

γ_c concrete reduction factor.

$$\xi = \left(1 + \sqrt{\frac{200}{d}}\right) < 2.0 \quad \text{(with d in mm)}$$

F_{cv}: Concrete shear effective strength in N/mm^2 with a value of $f_{cv} = f_{ck}$, being f_{cv} lower than 15 N/mm^2 in the case if indirect concrete control.

f_{ck}: Concrete compressive strength in N/mm^2.

f_{ck} values lower than 100 N/mm^2 will be adopted.

ρ_l: Steel ratio of the main longitudinal reinforcement, active and passive, anchored at a distance equal or higher than “d”.

A_α: Area per unit length of each steel reinforcement group which forms an angle α with the piece directrix.

$f_{y\alpha,d}$: Calculated strength for the reinforcement $A_{\alpha.}$

Finally, the theoretical deflections at mid-span have been also calculated for all the load states using the EHE method and the EC-2 method. The main difference between them is the inertia considered.

Deflection in the EHE-08 is calculated considering a weighted intermediate inertia between the gross inertia and the cracking inertia. The weighting factor is the cubed ratio of the cracking moment to the applied bending moment.

In contrast, deflection in the EC-2 is calculated as a weighted average of the deflection considering the non-cracked section and the deflection considering the cracked section. This weighted average depends on the squared ratio of the cracking moment to the applied moment.

3.3. Finite element analysis (FEA)

Computational simulations based on the finite element method (FEM) considering the real scales size of the tested RC were performed using Abaqus/Explicit. In the models, three dimensional hexahedral elements (Abaqus C3D8) were considered for the concrete sections, while all the steel reinforcement was modeled using beam elements (Abaqus B31). In addition, a rigid interaction (i.e. no slipping allowed) was assumed between the concrete and the steel bars. After mesh convergence analyses it was determined to use 7800 hexahedral elements and 3284 beam elements in the flexural test models, and 7800 hexahedral elements and 1788 beam elements in the case of shear test models. Deflections in the simulations of both tests were obtained by tracking the displacement of a reference point located mid-span of the beams.

A plastic damage model was assumed to model the concrete behavior. This model assumes that the main failure modes in concrete are tensile cracking and compressive crushing. Consequently, the tensile behavior of the concrete is assumed to follow a linear response characterized by the elastic modulus until reaching the tensile failure strength σ¬t, where σ¬t is assumed to be 7% of the compressive strength σ¬c. In addition to that, one cylindrical sample of each concrete was tested by split test (also named Brazilian test). It was observed that our assumption for the tensile failure strength is very close to the value obtained from the split test; see Table 4. Beyond the tensile failure strength, the formation of microcracks is represented with a linear softening of the stress-strain response characterized by a fracture energy 90 J/m^2 (90 N/m) [53]–[55] which corresponds to a typical value of fracture energy in conventional concrete. According to previous research [55]–[58], the fracture energy of recycled concrete can be as low as 50 J/m^2 and it showed a relation with the compressive strength. In the supplemental information, we show a comparison of the simulations considering both values (90 J/m^2 and 50 J/m^2). As observed in these figures the major effect of reducing the fracture energy corresponds to a change in the deflection at failure. However, the overall behavior of the beams is similar. Note that, a fracture energy of 50 J/m^2 is an extreme case (very low value) and, for our concretes we will not expect such a huge drop of the fracture energy according to the literature [55]–[58]. The compressive behavior is assumed to follow a linear response with elastic modulus *E* up to $\sigma_{c.}$ Beyond this point, the material is assumed to follow a perfectly plastic response. The values for *E*, σ_c, and σ_t used in each of the different mixes are reported in Table 4. In the case of the steel, it is assumed to follow a linear perfectly plastic response characterized by *E* = 200 GPa and σ_y = 500 MPa.

Table 4. Properties of concrete used on FEA

Property / Mixture	M-0	M-20	M-35	M-50
Compressive strength 28 days (MPa)	64.8	62.9	58.2	56.5
Split test (MPa) – One sample only	4.3	4.5	4.2	4.3
Tensile strength (7% of compressive strength) (MPa)	4.5	4.4	4.1	4.0
Modulus of elasticity 28 days (MPa)	29000	27500	26000	24000

4. Results

4.1. Experimental results

4.1.1. Mechanical and physical properties

- *Density of concrete mixes*

Table 5 shows the mean density of hardened concrete. It was measured following the standard EN 12390-7:2009 [59]. The density was slightly affected by the replacement of recycled aggregate. The decrease in density of M-50 in comparison with the density of the reference concrete was less than 2%.

Table 5. Average density

Concrete	Density (Kg/m^3)
M-0	2274
M-20	2250
M-35	2248
M-50	2244

- *Compressive strength and Modulus*

Table 6 shows the compressive strength and the modulus of elasticity at 28 days. As expected, the higher the amount of recycled aggregate used, the lower the mechanical property (compressive strength or modulus). For all the eco-concretes studied, the loss percentage of Modulus is higher than the loss percentage of compressive strength, but the difference between them is not high. With a replacement of 50% of the total amount of aggregate, and considering of M-0 as a reference, the loss percentage is around 13% of compressive strength and around 17% of Modulus. This means that, even with a 50% of fine and coarse recycled aggregate, the mechanical properties studied are not dramatically affected: a reduction of 13% for the compressive strength and 17% for the elastic modulus in comparison with the same properties of reference concrete without recycled aggregate.

Table 6. Mechanical properties

Property / Mixture	M-0	M-20	M-35	M-50
Compressive strength 28 days (MPa)	64.8	62.9	58.2	56.5
Modulus of elasticity 28 days (MPa)	29000	27500	26000	24000

4.1.2. Flexural strength in the real scale test.

Figure 4 shows the correlation between applied load and deflection registered in the flexural test of the beams tested. The beams with concretes M-35 and M-50 register for the same load a higher deflection than the registered in beams with concrete M-0 and M-20. It is also noted that the beams without recycled aggregate and with a 20% of recycled aggregate did not show relevant differences in the Load-Deflection behavior. This is an important observation because it means that with a replacement level of 20% of the total amount aggregate by fine and coarse recycled aggregate, the Load-Deflection behavior for the eco-concrete does not change with respect to the reference (M-0). We note that most of the current standards do not allow the use of fine recycled aggregate in structural concrete. Standards such as EHE-08 [3] only allow up to 20% of the coarse aggregate to be replaced by coarse recycled concrete aggregate without modifying the calculations. As mentioned before, we considered the percentage of replaced aggregate as the percentage over the total amount of aggregate, therefore, our M-20 has a higher amount of recycled aggregate and it is not in compliance with EHE-08.

The experimental deflection at mid-span in yielding in the beam made with M-50 is around a 10% higher than the deflection in the beam with the reference concrete (Table 7). In Failure, the experimental deflection at mid-span could not be measured in the beams with M-20 and M-35 concretes because the beams failed in a way that made not possible to get the last measurement of the deflection. The changes in the experimental bending moment at mid-span due to the use of recycled aggregate are negligible and they do not have a clear trend, both for yielding and failure.

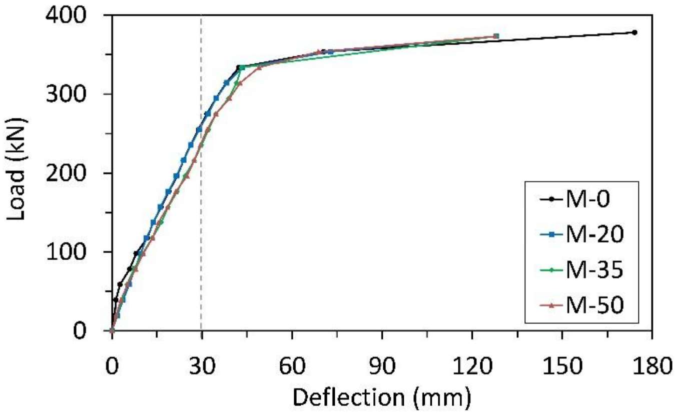


Figure 4. Real results of the flexural tests

Table 7. Values of the flexural test

	Property	M-0	M-20	M-35	M-50
Yielding	Experimental deflection at mid-span (mm)	41	40	43	45
	Experimental bending moment at mid-span (kN·m)	393	381	399	386
	Theoretical bending moment at mid-span (kN·m)	379	378	377	376
Failure	Experimental deflection at mid-span (mm)	174.1	> 128	> 128	127.7
	Experimental bending moment at mid-span (kN·m)	451.9	443.0	444.4	447.1
	Theoretical bending moment at mid-span (kN·m)	432	431	428	428

4.1.3. Shear strength in the real scale test.

Figure 5 shows the Load – Deflection behavior obtained for the different concretes during testing for the shear test. The represented load is the load applied by the actuator during the shear test (Figure 2.b). The results show that there is an influence of the replacement percentage of recycled aggregate in the behavior. Table 8 summarizes the maximum deflection and maximum shear strength before failure for each beam. In addition, there is no influence of the recycled aggregate on the experimental deflection at mid-span in failure. However, we found a trend of the influence of the recycled aggregate on the maximum shear strength; the higher the level of recycled aggregate is, the lower the maximum experimental shear strength at the end of the beam.

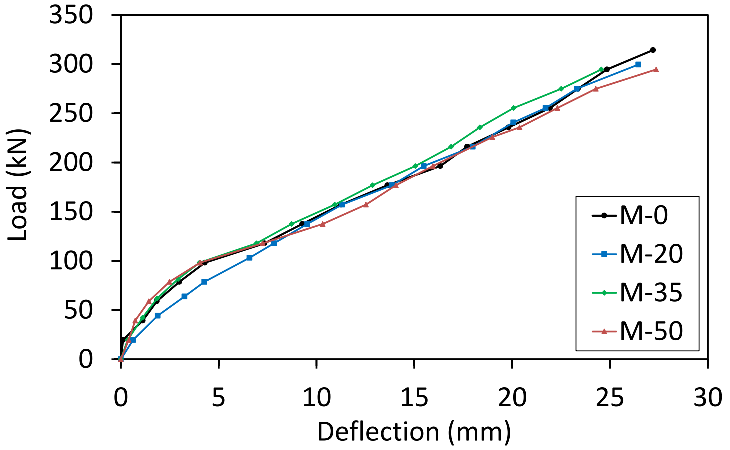


Figure 5. Real results of the shear tests

Table 8. Values of the shear test

Property (Failure)	M-0	M-20	M-35	M-50
Experimental deflection at mid-span (mm)	27.2	26.5	24.6	27.4
Experimental shear at the end of the beam (kN)	167.7	160.5	158.1	157.8

4.2. Theoretical results

Figure 6 shows the analytical results of the flexural strength test (Deflection vs Load), according to the Eurocode standard (Figure 6.a) and according to the EHE-08 standard (Figure 6.b), of the beams with each concrete (M-0, M-20, M-35 and M-50). According to these theoretical results, a 20% of replacement of the total amount of natural aggregate by recycled aggregate does not affect the curves Load-Deflection which overlap for the beams with reference concrete (M-0) and concrete with 20% of recycled aggregate (M-20). Higher percentages of replacement (35% and 50%) imply a reduction of the load value for a given deflection. This fact was also observed on the real scale experiments (Figure 4). According to the Eurocode standard EC-02 [60], a deflection of 30 mm corresponds to a load for M-0 of 287 kN, but for M-50 the corresponding load for the same deflection is 271 kN (Figure 6.a).

Figure 7 shows the results of the shear strength test (Deflection vs Load) of beams made of each studied concrete, according to the Eurocode standard (Figure 7.a) and according to EHE-08 standard (Figure 7.b). The beam M-20, with a 20% of recycled aggregate, is really close to the reference concrete beam (M-0) but they do not overlap. With higher percentages or recycled aggregate, the difference between the curves Load-Deflection is larger, in comparison with reference beam.

Table 9 summarizes the yielding and failure theoretical bending moments at mid-span and the theoretical shear at the end of each beam studied at failure.

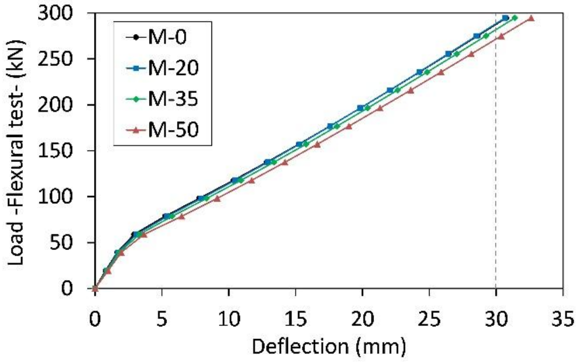


Figure 6.a) Theoretical results of the flexural strength [EC-2]

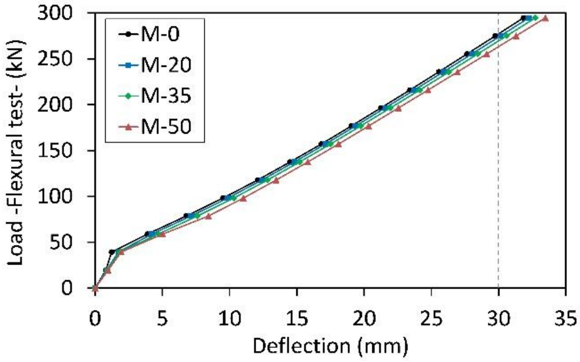


Figure 6.b) Theoretical results of the flexural strength [EHE-08]

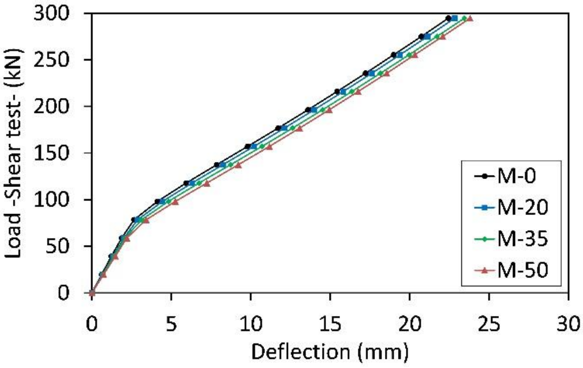


Figure 7.a) Theoretical results of the shear strength[EC-2]

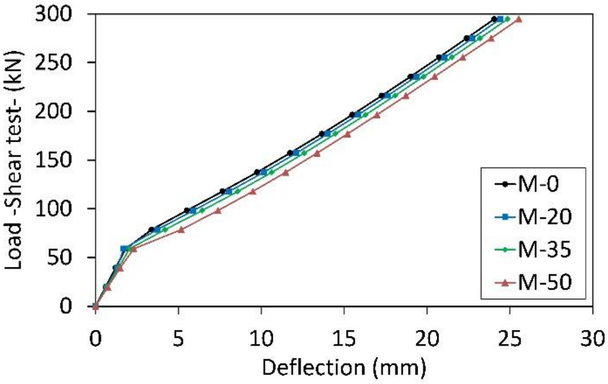


Figure 7.b) Theoretical results of the shear strength [EHE-08]

Table 9. Theoretical values of the bending moment and shear

Property	M-0	M-20	M-35	M-50
Theoretical bending moment at mid-span (kN·m) [Yielding]	379	378	377	376
Theoretical bending moment at mid-span (kN·m) [Failure]	432	431	428	428
Theoretical shear at the end of the beam (kN) [Failure]	176.6	172.0	165.4	163.0

4.3. FEM results

4.3.1. Results of flexural test using FEM

Figure 8 shows the pattern of cracks as a result of the FEM model at two steps: plastic strain after 33.05 mm of deflection (Figure 8.a) and after a deflection of 120 mm (Figure 8.b). It also shows the comparison between these crack patterns and the real crack pattern resulting from the flexural strength test on real scale beams. All the images belong to the flexural test of the deformed beam M-0 with cracks. Figure 9 shows the Load-Deflection diagram resulting from the application of FEM models. According to these results, for the same deflection, the higher the replacement level of recycled aggregate is, the lower the load, but the differences between the concretes studied are not significant (less than 10%).

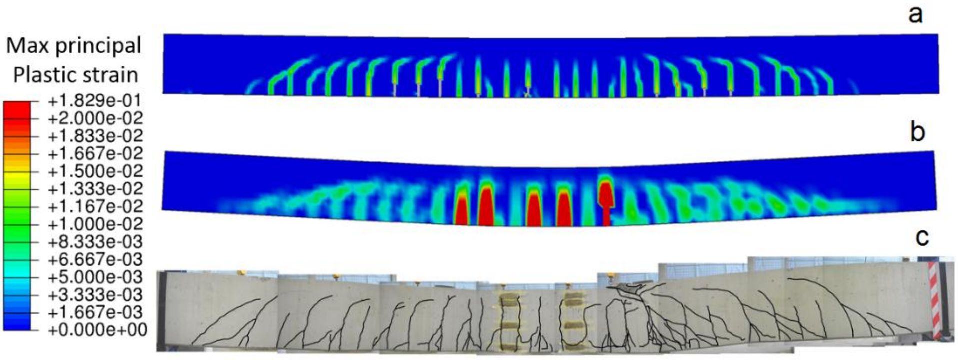


Figure 8. Flexural test of beam with concrete M0: (a) FEA model with principal plastic strain after a deflection of 33.05 mm. (b) FEA model with principal plastic strain after a deflection of 120 mm. (c) photography of cracking pattern at flexural failure.

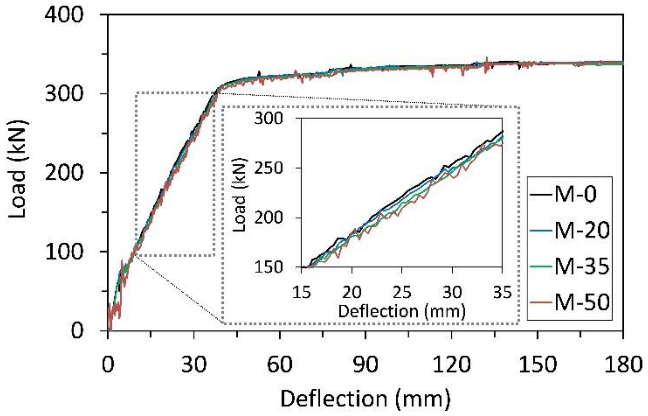


Figure 9. Load - Deflection using FEM results of flexural strength

4.3.2. Results of shear test using FEM

Figure 10 shows the pattern of plastic deformation after applying a defection of 25.4 mm. Figure 10 also shows a picture of real scale shear test. The figure shows that the shape of the crack pattern of the real test matches with the FEM results. Both images belong to the shear test of the deformed beam M0 with cracks. Figure 11 shows the shear Load-Deflection diagram resulting from the application of FEM models. According to these results, for the same deflection, the higher the replacement level of recycled aggregate is, the lower the load. These differences are more relevant than the differences observed on the flexural test using FEM, but not higher than 20%.

Figure 10. Shear test of beam with concrete M0: FEA model with principal plastic strain after a deflection of 25.4 mm and detail photography of cracking pattern on one extreme of the beam at shear failure

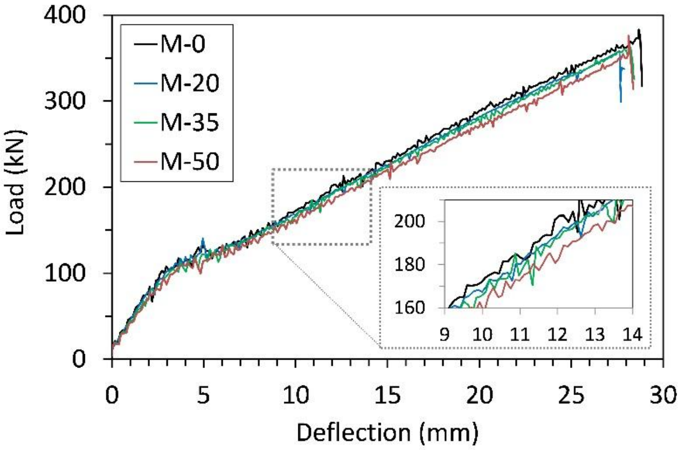
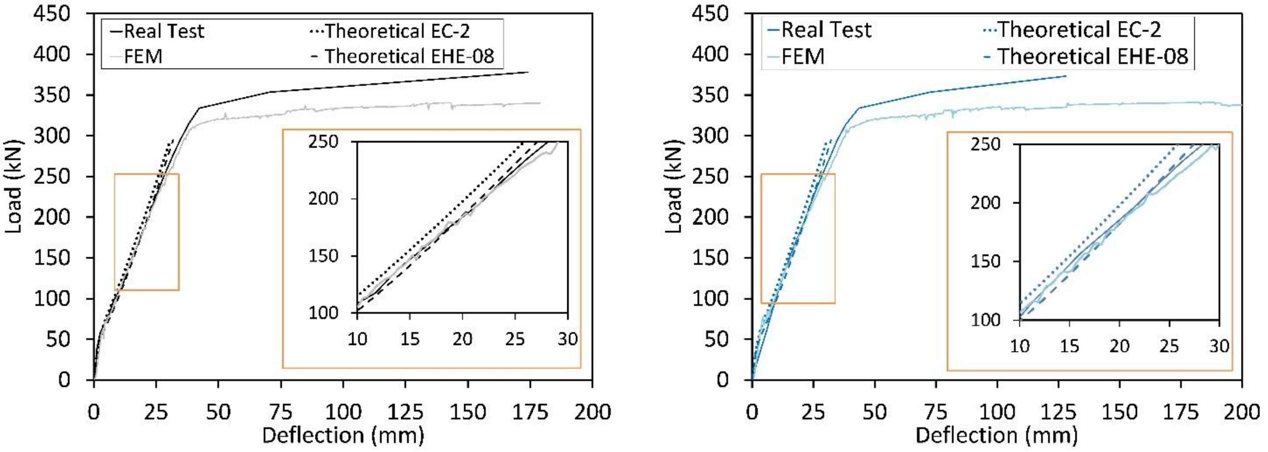


Figure 11. Load - Deflection using FEM results of shear strength

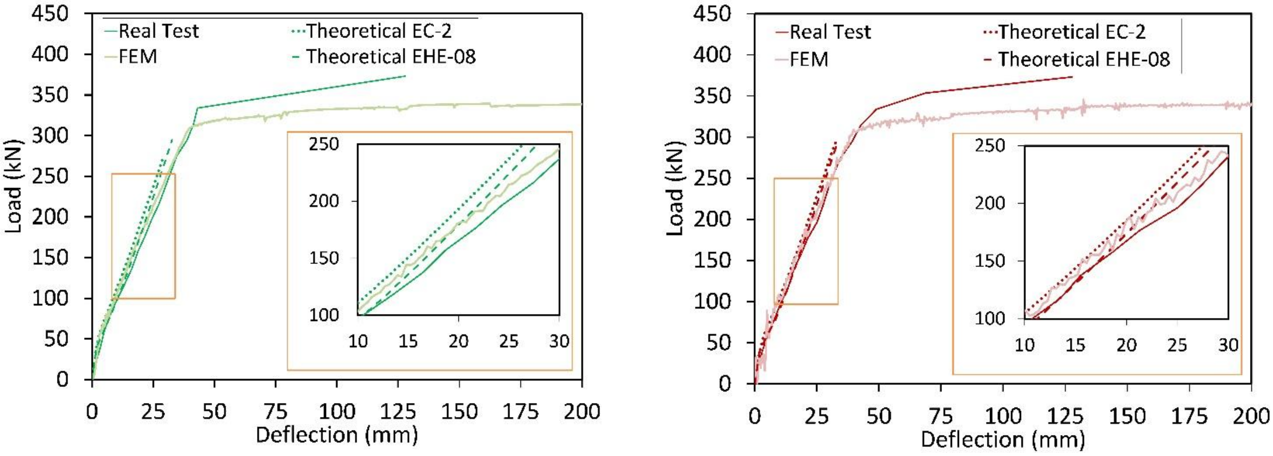
5. Analysis: Comparison between experimental, FEM and analytical results

5.1. Comparison on flexural test

Figure 12 shows the results comparison of real scale test, theoretical results according to two different standards and FEA results, for the flexural test of each concrete beam. As it can be observed, for all concretes, the higher the deflection is, the better the results of the simulations are in comparison with the theoretical models. In addition, it is remarkable that the theoretical models are overestimating the load when the deflection is higher than 25 mm in all the cases studied. The FEM models simulate the behavior of the beam during the elastic part of the test and underestimate the plastic moment, but it seems a very good approach.



a) M-0 b) M-20

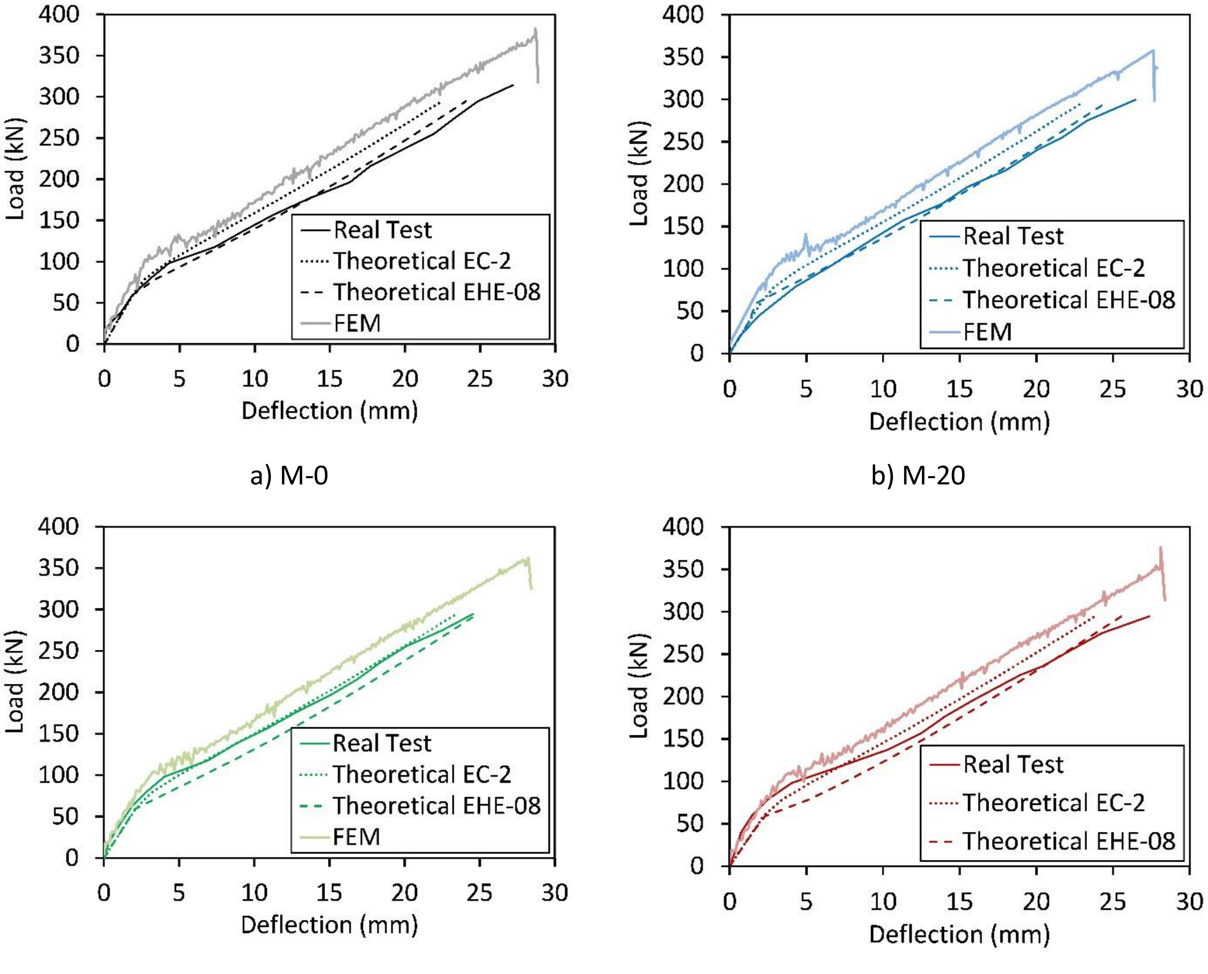


c) M-35 d) M-50

Figure 12. Comparison of FEM, analytical and experimental results [Flexural test]

5.2. Comparison on shear test

Figure 13 shows the comparison of the results of real scale test, theoretical results according to two different standards and FEA results, for the shear test of each concrete beam. The best estimation of this test was obtained applying the theoretical models. In particular, the EHE-08 estimation is the best for the beams without recycled aggregate (Figure 13.a) or with low replacement of natural aggregate by recycled aggregate (Figure 13.b). For higher replacement (Figures 13.c and 13.d), the theoretical approach of EC-2 has the same accuracy or even higher than the EHE-08 approach.



a) M-0

b) M-20

c) M-35

d) M-50

Figure 13. Comparison of FEM, analytical and experimental results [Shear test]

6. Discussion and conclusions

According to the experimental results, if 50% of the total aggregate is replaced by recycled concrete aggregate (fine and coarse), the resulting concrete presents a reduction of 13% in the compressive strength and 17% in the Modulus, with respect to the values of the reference concrete (without recycled aggregate). However, the experimental values of yielding and failure bending moments at mid span are not significantly affected (with a 50% replacement of the total aggregate, they suffered a detriment of 0.8% and 1.1%, respectively). The failure shear moment decreases 6% with the replacement of 50% of the total aggregate by recycled concrete aggregate. It was also observed that, the higher the level of recycled concrete aggregate is, the lower the maximum experimental shear strength at the end of the beam.

The theoretical Load-Deflection curves using EC-2 or EHE-08 Standards predicted the experimental results obtained on beams made of plain concrete and beams made of concrete with 20% replacement of fine and coarse recycled aggregate (M-20) with and error lower than 20%, in both cases. It is remarkable that this 20% of substitution corresponds to the 20% of the entire amount of aggregate (including fine and coarse). The EHE-08 recommends the use of the theoretical models for concretes with no more than 20% replacement of the coarse aggregate. In the case of M-20, the amount of recycled concrete aggregate represents more than 40% of the natural coarse aggregate of the reference concrete. Other standards do not allow any percentage of fine recycled concrete aggregate for structural concrete. Our results suggest that these restrictions are too conservative, at least from the mechanical behavior point of view.

For a higher percentage of recycled concrete aggregate (35%), it was observed that the theoretical models are overestimating the flexural load for a given deflection or, in other words, theoretical models are underestimating the deflection produced by a given flexural load. The proposed FEM models make better predictions in those cases. So, for percentages higher than 20% of the total aggregate, FEM methods or other methods should be necessary in addition to the theoretical calculations of standards (EC-2 and EHE-08). Whereas the prediction of Load-Deflection in the elastic branch using FEM has a negligible error in comparison with the real test, on the plastic regime, our FEM models underestimate the load with an error around 10% in all the cases studied (M-0, M20, M35 and M50).

In the case of shear tests, the FEM models are not improving the accuracy of the theoretical estimations. The best estimations were obtained applying the theoretical models. In particular, the EHE-08 estimation is the best one for the beams with percentages lower or equal to 20%. For higher replacement levels of recycled concrete aggregate, the theoretical approach of EC-2 has the same accuracy or even higher than the EHE-08 approach on the estimations of the relationship between load and deflection in shear tests.

Since the theoretical models predict with high accuracy the behavior of the beams in the shear test, regardless the percentage of recycled concrete aggregate, the FEM model for shear strength is not so necessary. The results suggest that the theoretical models can be applied for structures, regardless the percentage of recycled concrete aggregate, without losing accuracy.

The proposed FEM models are mainly useful to predict the flexural behavior of reinforced beams made of concrete with high replacement of recycled concrete aggregate, when the theoretical models start to lose accuracy, in comparison with the results of structures made of plain concrete or with a low replacement level of recycled concrete aggregate.

Note that this research is focused on the use of fine and coarse recycled aggregate for concrete from defective pieces of concrete produced in a precast plant. Other types of recycled aggregates, such recycled mixed aggregates, for example, from masonry, would need separate studies.

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Supplementary material
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SUPPLEMENTARY MATERIAL

In order to check how the potential variation of fracture energy due to the use of recycled aggregate could affect the results of our finite element simulations, Figures S1 (results of flexural test) and S2 (results of shear test) show the difference between the load-deflection curves from FEA in two cases: Assuming fracture energy 90 J/m^2, and assuming 50 J/m^2 (the lowest value observed in previous research [55]–[58]), for the beams made of concrete with recycled concrete aggregate.

As observed in these figures the major effect of reducing the fracture energy corresponds to a change in the deflection at failure. However, the overall behavior of the beams is similar and follows the trends observed in the experimental data.

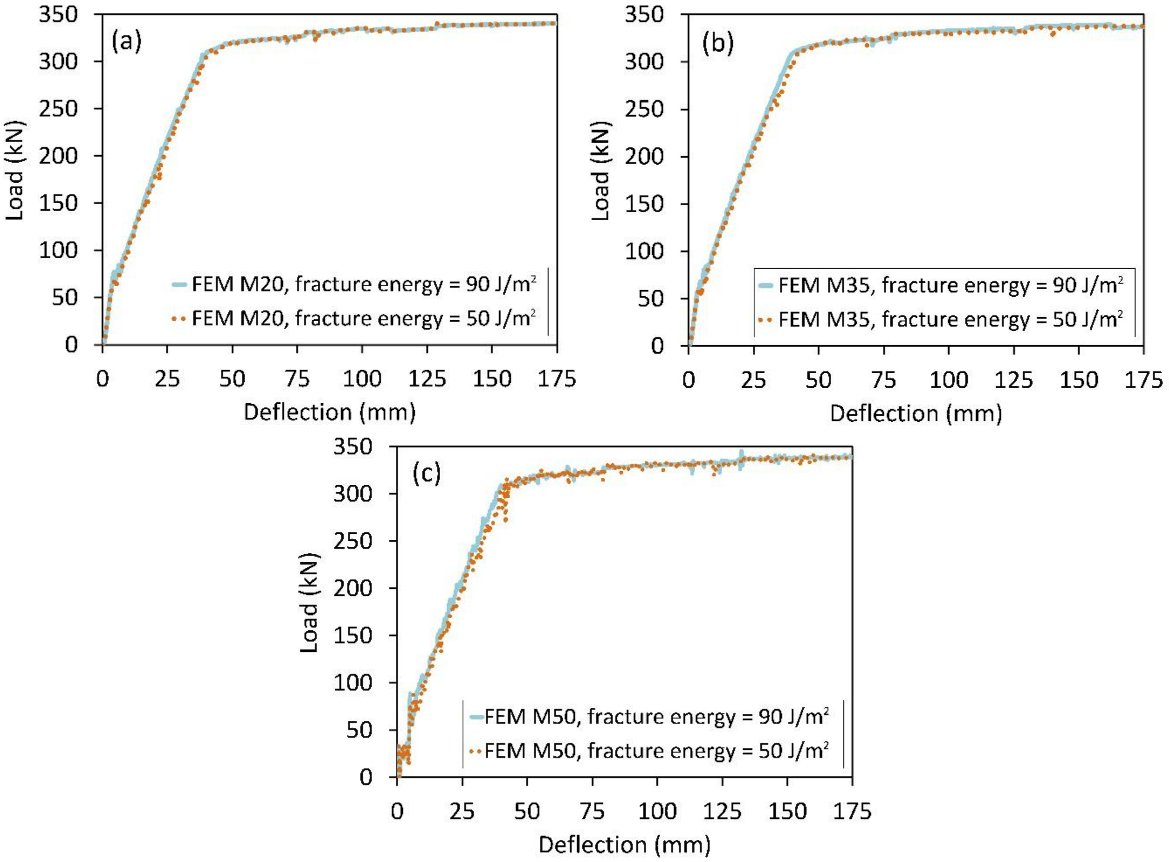

Figure S1. Comparison between Load-Deflection curves with different fracture energies [Flexural test]. (a) M-20, (b) M-35, (c) M50.

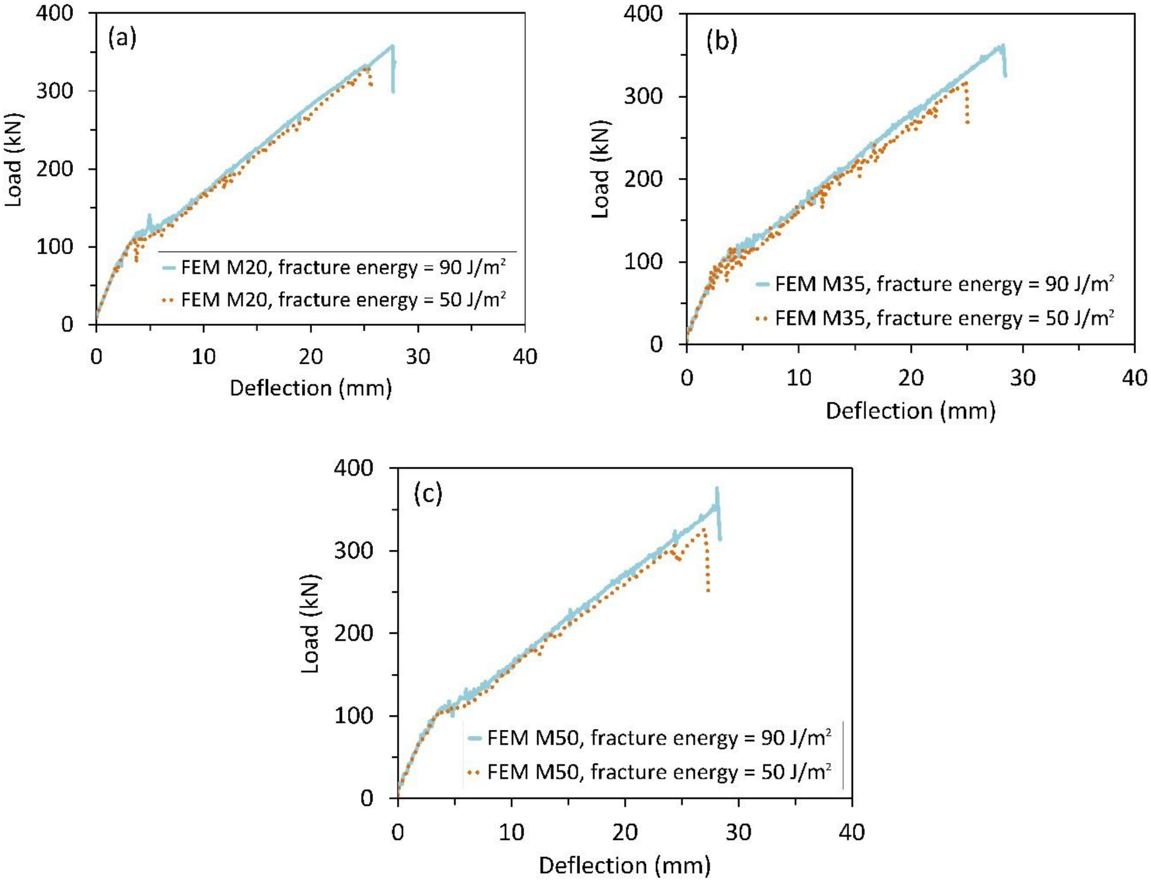

Figure S2. Comparison between Load-Deflection curves with different fracture energies [Shear test]. (a) M-20, (b) M-35, (c) M50.

In addition, note that, note a fracture energy of 50 J/m^2 is an extreme case and, for our concretes we do not expect such a huge drop of the fracture energy according to the literature [55], [56]. Garcia-Gonzalez et. al. [55] observed that, for a reference concrete (no recycled aggregates) with fracture energy 99.6±8.6 N/m, the concrete with 50% of replacement of recycled aggregate had a fracture energy of 89.7±8.4 N/m. This research also concludes that there exists a direct relationship between compressive strength and fracture energy of recycled aggregate concrete; since the studied concrete with the highest amount of recycled aggregates (M-50 with 50% of recycled aggregates) presents only a detriment of less than 13% of the compressive strength, we do not expect extreme changes of the fracture energy of the different studied concretes. Gesoglu et. Al. [56] showed also a direct relation between compressive strength at 56 days and fracture energy. They proposed a regression analysis with the next equation as result:

$$\mathrm{G_F} = 0.059 \cdot \mathrm{f_c}^{1.75} \tag{Eq.s1}$$

Here, G_F is the total fracture energy (N/m) and f_c is the mean cube compressive strength at 56 days (MPa).

Therefore, using our compressive strength data at 28 days, instead of the compressive strength at 56 days, the expected fracture energy for the reference concrete M-0 is 87 N/m, and for the concrete with

50% of recycled aggregate (M-50) is 69 N/m. Both values would be higher if we use the right data (compressive strength at 56 days) to apply this equation.