

Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete

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Abstract

In this study recycled coarse aggregates obtained by crushed concrete were used for concrete production. Four different recycled aggregate concretes were produced; made with 0%, 25%, 50% and 100% of recycled coarse aggregates, respectively. The mix proportions of the four concretes were designed in order to achieve the same compressive strengths. Recycled aggregates were used in wet condition, but not saturated, to control their fresh concrete properties, effective w/c ratio and lower strength variability. The necessity to produce recycled aggregate concrete with low–medium compressive strength was verified due to the requirement of the volume of cement. The influence of the order of materials used in concrete production (made with recycled aggregates) with respect to improving its splitting tensile strength was analysed. The lower modulus of elasticity of recycled coarse aggregate concretes with respect to conventional concretes was measured verifying the numeral models proposed by several researchers.

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1. Introduction

To obtain good quality concrete using recycled aggregate it is necessary to follow the minimum requirements defined by the BCSJ [1], RILEM [2], DIN 4226.100 [3], and prEN 13242:2002 [4]. Acceptable properties of aggregates are an elemental base for concrete quality, however adequate mix proportions and concrete production methods are highly important in concrete quality too. Recycled aggregates are composed of original aggregates and adhered mortar. The physical properties of recycled aggregates depend on both adhered mortar quality and the amount of adhered mortar. The adhered mortar is a porous material, its porosity depends upon the w/c ratio of the recycled concrete employed [5]. The crushing procedure and the dimension of the recycled aggregate have an influence on the amount of adhered mortar [6–9]. The density and absorption capacity of recycled aggregates are

affected by adhered mortar and they must be known prior to the utilization of recycled aggregates in concrete production in order to control properties of fresh and hardened concrete. The absorption capacity is one of the most significant properties which distinguishes recycled aggregate from raw aggregates, and it can have an influence both on fresh and hardened concrete properties. Some researchers suggest a limit of 30% of recycled aggregate in order to maintain the standard requirements of 5% of absorption capacity of aggregates for structural concrete [10,11].

The increased absorption of recycled aggregate, means that concrete made with recycled coarse aggregates and natural sand typically needs 5% more water than conventional concrete in order to obtain the same workability [12–17]. If recycled aggregates are employed in dry conditions the concrete's workability is greatly reduced due to their absorption capacity. Some researchers argue that the recycled aggregates should be saturated before use [18].

In general the workability of recycled aggregate concretes is affected by the absorption capacity of the recycled aggregates. The shape and texture of the aggregates can also affect the

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workability of the mentioned concretes. This depends on which type of crusher is used [19].

With respect to compressive strength, concrete made with 100% of recycled coarse aggregate with lower w/c ratio than the conventional concrete can have a larger compression strength. When the w/c ratio is the same the compression strength of concrete made with 100% of recycled aggregate is lower than that on conventional concrete [20].

In case of recycled aggregate concrete it will be necessary to add more cement in concrete made with 100% of recycled aggregate in order to achieve the same workability and compression strength as conventional concrete. The employment of different qualities of recycled aggregate in concrete production brings about an increase in the compressive strength variation coefficient [21]. Any variation in concrete production or in the properties of the constituents used produces a variation of strength in the resultant concrete.

This paper examines the difficulty of obtaining the same high compressive strength in concrete with high percentages of recycled aggregates and conventional concrete. Four different dosages were employed in the production of the four mixes. The first concrete mix was a control concrete (CC), in this case raw, fine and coarse aggregates were used. In the second concrete mix, (RC25) 25% of the coarse raw aggregates were replaced by recycled coarse aggregates, in the third concrete mix (RC50) 50% of the coarse raw aggregates were replaced by recycled coarse aggregates and in the fourth one (RC100) 100% of the raw coarse aggregates were replaced by recycled coarse aggregates. Limestone sand (S) was used as fine aggregate in all concrete mixes. The utilization of recycled sand was avoided, due to its absorption capacity, which would no doubt produce a shrinkage effect [21]. The quantity of adhered mortar increases with the decrease of size of the recycled aggregates [22]. Once a similar compressive strength had been reached in the four concrete mixes by mix design, the tensile strength and modulus of elasticity of the recycled aggregate concrete were measured. The experimental values of modulus of elasticity were compared with different numerical proposals. The influence of recycled aggregate content on variability of compressive strength was also determined.

2. Materials and experimental details

2.1. Materials

The recycled aggregates employed to produce the concrete were taken from a waste recycling area. They were obtained by crushing unknown waste concrete by use of an impact crusher. The composition of recycled aggregates determined by visual inspection were defined as 92.1% crushed concrete (49.1% of original aggregate plus adhered mortar and 43% of original aggregates), 1.6% of ceramic aggregates and 5.3% of Bituminous and 0.8% of other. Recycled and natural coarse aggregates, named RA and A respectively, had the same fraction size, 4/10 mm (1), 10/16 mm (2) and 16/25 mm (3). Aggregates sieve distribution was determined in accordance with code UNE-EN 933-1,2.

The high percentage of clean aggregates (without adhered mortar) suggests that the original concretes (from which the recycled aggregates were obtained) had low strengths. The quantity of adhered mortar was approximately 20% for fraction 10/25 mm and approximately 40% to 4/10 mm fraction. The density, absorption and shape index of raw and recycled aggregates were respectively, density 2.67 kg/dm³ and 2.43 kg/dm³, absorption 0.886% and 4.445%, and shape index 25% and 28% determined in accordance with EN specifications.

CEM I 52.5R, a high quality, high strength rapid-hardening Portland cement was used in all four mixes.

In order to achieve the same workability in all four different concretes, Glenium C313, superplasticizer was used.

2.2. Experimental details

2.2.1. Dosage system and workability of fresh concrete

The Bolomey dosage method [23,24] was used in the mixing of both concretes, the dosage calculations began with the cement quantity and w/c ratio required. The aggregates percentage in each dosage was calculated by the Bolomey analytical method (determining the volume of each fraction). The weight of each fraction employed in the concrete mix was calculated by its density. The humidity of the aggregates was measured and their absorption capacity considered at the moment of concrete production. The water content or the humidity of the aggregates was measured according to EN 1097-5:2000. The mass of water content is the difference between the material mass in the situation of using and the dry mass. The humidity of recycled aggregates reduces the water absorption capacity of them and they were used with 3.5% of humidity. In the case of limestone sand (which has a fastest capacity for water absorption) it was imperative to calculate the amount of water to be added to the mix, so as not to affect the effective w/c ratio and maintain the concrete's plasticity.

Due to its high absorption capacity recycled coarse aggregate must be wet before its employment in making concrete. If the recycled coarse aggregate is not humid, it would absorb water from the paste thus losing both its workability in the fresh concrete, and also the control of the effective w/c ratio in the paste.

In this study, recycled coarse aggregates were wetted by a sprinkler system the day before they were used and they were covered with a plastic sheet in order to maintain their high humidity. A recommended level of humidity could be 80% of the total absorption capacity, however the most important factor is that the aggregates employed are wet in order to reduce their absorption capacity. In this case the mechanism could be that recycled aggregate that had a moderate initial moisture content absorbed a certain amount of free water and lowered the initial w/c in the ITZ at early hydration. Newly formed hydrates gradually filled the region processes effectively improved the interfacial bond between the aggregates and cement [25]. One should note, however, that the recycled aggregates should not be saturated, as that would probably result in the failure of an effective interfacial transition zone between the saturated recycled coarse aggregates and the new cement paste. Barra

Table 1
Mix proportions of control (CC) and recycled aggregates concrete (RC 100)

	S (kg)	A1 (kg)	A2 (kg)	A3 (kg)	Cement (kg/m ³)	Additive (%)	Water (kg)	Effective w/c
CC	710.5	346.5	290.4	570.0	325	1.28	178.7	0.50
	S (kg)	RA1 (kg)	RA2 (kg)	RA3 (kg)	Cement (kg/m ³)	Additive (%)	Water (kg)	Effective w/c
RC100-1	660.7	422.2	300.7	383.9	325	2	178.7	0.50
RC100-2	613.9	433.7	296.8	378.9	345	2	189.7	0.43
RC100-3	586.8	448.5	298.0	380.3	365	2	186.5	0.40
RC100-4	586.8	448.5	298.0	380.3	365	2	186.6	0.4
RC100-5	660.7	422.2	300.7	383.9	325	0.58	178.7	0.52

S: Sand; A1, A2 and A3: natural coarse aggregate 4/10 mm, 10/16 mm and 16/25 mm, respectively.

de Olivera and Vázquez [26], note a slight decrease especially in flexural strength of the concrete made from saturated recycled aggregates. In the production of the recycled aggregate concretes studied, humid recycled aggregates were used.

The fresh concretes were made with 8–10 cm slump. Although the recycled aggregates were humid (normally recycled aggregate concretes have less workability) the amount of additive used was slightly higher than that used for conventional concrete. The workability of fresh concrete was determined by a slump test, in accordance with UNE 83313:90.

2.2.2. Concrete production process

Four concretes, CC, RC25, RC50 and RC100, were produced all of them with the same compressive strength. In order to define the suitable mixes, testing began by producing the two extreme concretes, control concrete (CC) and concrete made with 100% of recycled coarse aggregates (RC100). Two stages were needed to achieve the objective of producing a CC concrete and an RC100 concrete with the same compression strength.

In stage 1, the CC concrete was produced using 325 kg of cement/m³ of concrete with an effective w/c ratio of 0.50. However, in order for the RC100 concrete to achieve a similar high compression strength to that of the CC concrete it would be necessary to use approximately 20–30% more amount of cement. Therefore in stage 2 the cement quantity employed in the CC concrete was reduced to 300 kg of cement/m³ of the concrete mix, with an effective w/c ratio of 0.55, while the same conditions were maintained for the production of the RC100 concrete as those detailed in stage 1 (325 kg of cement/m³ of concrete and an effective 0.5 w/c ratio). Once the compressive strength of CC and RC100 concretes was the same, the production of RC25 and RC50 concretes was carried out. RC25 was produced using the same mix proportion of CC. The effective w/c ratio of RC50 was higher than that of RC100 and lower than that of CC. The mixes were defined by linear relationship and were determined experimentally.

The stages 1 and 2 concretes were produced in a vertical axle mixer by adding the materials manually. The materials were always added in the same order; first the cement and water were added and mixed for 1 min. After which the aggregates were

added, starting with the finer aggregates and terminating with the larger ones, the cement, water, sand and aggregates were mixed for a further 1 min before adding the additive. The complete mixture was then mixed for 1 min more.

For each mixture, 150-mm-cube specimens were kept in their molds for 24 h. After demolding, they were stored in the humidity room at 21 °C with 100% humidity until 2 h before testing them at 7 days and 28 days. All the test elements were kept in the same conditions before testing and the compression strength of the concrete was determined according to those laid out in UNE 83-304-84.

After the four concrete mixes got the same compressive strength (defined as stage 2) they were produced using an automatic adding mixing machine. The concrete production order is different in this type of machine with respect to that of machines where the materials are added manually; in the first step of operating the fine and coarse aggregates were mixed for 30 s. The second step consisted of adding the cement and a further mixing of materials for 30 s. The third step consisted of adding water to the cement and aggregate mix and mixing for 1 min. The fourth and final step consisted of manually adding the superplasticizer and a further mixing of all component materials for 1 min before the mixing machine was stopped. The mechanical properties of all concretes produced by manual and automatic machine were determined.

3. Experimental results

3.1. Production stage 1. Mix proportions for HC and HR100

Five dosages were used for 100% recycled aggregate concrete to get the compressive strength of CC, see Table 1. As Fig. 1 illustrates, the compressive strength of RC100 increases when the w/c ratio is reduced. The evolution of different recycled concrete strengths was almost parallel or at least very similar in the last 21 days of the 28 day allowed for curing. The RC100-3 and RC100-4 concrete mixes had the same compressive strength to that of the CC mix after 7 days of curing, the great difference being noted after 28 days. The 365 kg of cement/m³ of concrete was too low for RC100 in order to obtain

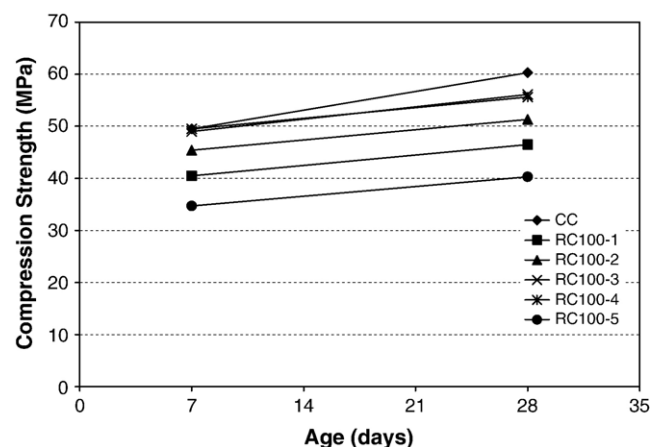


Fig. 1. Concrete strength's evolution with the age.

Table 2

Definitive dosage for control concretes (CC), 25% recycled aggregate concrete (RC25), 50% recycled aggregate concrete (RC50) and 100% recycled aggregate concrete (RC100)

	S	A1	RA1	A2	RA2	A3	RA3	Cement	Additive %	W	Effective w/c
CC	765.1	332.7		295.1		579.2		300	0.97	165	0.55
RC25	765.1	249.5	72.8	221.3	64.6	434.4	128.3	300	0.79	165	0.55
RC50	739.0	172.1	150.6	147.4	129.2	289.4	256.6	318	0.84	165	0.52
RC100	683.2		425.8		306.4		391.2	325	1.38	162	0.50

S: Sand; A1, A2 and A3: natural coarse aggregate 4/10 mm, 10/16 mm and 16/25 mm, respectively. RA1, RA2 and RA3: Recycled coarse aggregate 4/10 mm, 10/16 mm and 16/25 mm, respectively.

Aggregates, cement and water are given in mass (kg) for 1 m³ of concrete.

the same compressive strength of the CC mixes. However the cement amount required for the high compressive strength concrete was considered high and consequently the dosage of the CC concrete was changed from 325 kg to 300 kg of cement/m³ of concrete with 0.55 effective water/cement ratio. As it is mentioned above the recycled aggregates were used wet and this produced controllable variables concrete, as shown in the RC100-3 and RC100-4 mixes where the concretes' properties were quite easy to repeat.

3.2. Production stage 2. Mix proportions of CC, RC25, RC50 and RC100

The dosages for CC, RC25, RC50 and RC100 concretes are given in Table 2. With these dosages, similar compressive strengths were obtained for all concretes as illustrated in Fig. 2. The RC25 concrete mix achieved the same properties as the CC concrete mix maintaining the mix proportions and its production order the same. Several changes were carried out in the RC50 and RC100 dosages in order to achieve the same compressive strength to that of the CC mix. The RC50 mix needed 6% more cement mass than the CC and the effective w/c ratio was reduced to 0.52. For RC100 concrete, 8.3% more cement was needed to achieve the CC's compressive strength with 0.5 effective w/c ratio.

There was an increase of approximately 12–15% of compression strength in the recycled aggregate concrete (RC25, RC50 and RC100) when the conventional concrete

(CC) strength increased by approximately 20% in the last 21 days of the 28 day curing period. According to Salem and Burdette [27] the observed increases in the compressive strength of RC is due to the rough texture and absorption capacity of the adhered mortar in recycled aggregates that provides better bonding and interlocking between the cement paste and the recycled aggregates themselves compared with those of CC.

Cylinder test elements were produced from defined mix proportions in order to determine the compression strength, splitting tensile strength and modulus of elasticity of the four concretes produced during their 28 days of curing, see Table 3.

The splitting tensile strength was similar in all of the concretes produced, although as Table 3 shows, the splitting tensile strength of the recycled aggregate concrete was higher than that of the CC concrete. This was due to the absorption capacity of the adhered mortar present in the recycled aggregate (they were wetted by a sprinkler system, with high humidity but no saturated) and the effectiveness of the new interfacial transition zone of the recycled aggregate concrete [27]. According to Sague-Crentsil et al. [28] the absence of any detrimental effect on recycled concrete tensile strength is partly indicative of good bond characteristics between aggregate and the mortar matrix. Recycled aggregate produced splitting tensile strengths higher than that obtained using natural aggregate [29].

The tests were, conducted according to; UNE 83-304-84: compression strength, UNE 83-306-85: tensile strength and UNE 83-316-1996: modulus of elasticity.

3.3. Properties of concretes produced by automatic mixer machine

Once the adequate dosage was found in stage 2, the concrete production was applied to industrial volume employing an

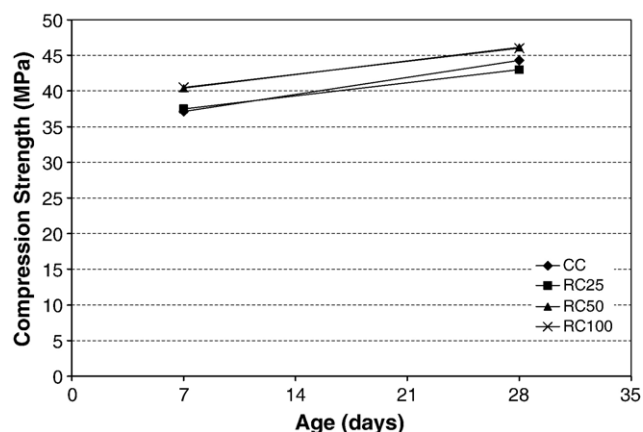


Fig. 2. Definitive concretes strengths at 7 and 28 days in cubic tests elements.

Table 3

Mechanical properties of cubic test elements at 28 days of curing

	Density (kg/dm ³)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (MPa)
CC	2.42	29	2.49	32,561.7
RC25	2.40	28	2.97	31,300.4
RC50	2.39	29	2.70	28,591.7
RC100	2.34	28	2.72	27,764.0

Table 4
Mix proportions for industrial volume

	S	A1	AR1	A2	AR2	A3	AR3	Cement	Additive (%)	Water	Effective w/c
CC	765.1	332.7		295.07		579.2		300	1.40	165	0.55
RC25	765.1	249.5	72.8	221.3	64.6	434.4	128.3	300	1.66	165	0.55
RC50	739.0	172.1	150.6	147.4	129.2	289.4	256.6	318	1.90	165	0.52
RC100	683.2		425.8		306.4		391.2	325	1.90	162	0.50

The w/c ratio is an effective value in the paste. Aggregates, cement and water are given in mass (kg) for 1 m³ of concrete.

S: Sand; A1, A2 and A3: natural coarse aggregate 4/10 mm, 10/16 mm and 16/25 mm, respectively. RA1, RA2 and RA3: Recycled coarse aggregate 4/10 mm, 10/16 mm and 16/25 mm, respectively.

automatic mixing machine and its influence in concrete properties was analysed.

The dosage used is shown in Table 4. It is important to mention that in this case, the machine employed had a much larger volume capacity for mixing as well as operating at a higher speed. In this case some more superplasticizer was used to maintain the same workability that had been derived from using a manual machine. In an automatic machine the free water is absorbed as it contacts directly with the recycled aggregate and cement mix. However in manual machine the water first comes into contact with cement therefore, the free water was lower. In this case the workability of the fresh concrete was also around 8–10 cm and the recycled aggregates were always employed wet, with approximately 80% of absorbed water.

The concretes' properties were determined at 28 days and at 6 months and the results are shown in Table 5.

The compression strength's evolution time was different in all concretes. It was discovered that with respect to CC concrete, its compression strength value at 28 days increased over the following 5 months and at 6 months there was a 19% increase. The same increase in compression strength was also obtained in RC25 concrete. However, when the percentage of recycled aggregate employed in the mix was increased the increase in compressive strength measured at 6 months was smaller. This could be a consequence of the accumulation of cement the aggregates' surface producing very low w/c ratio and effective interfacial transition zone (ITZ). According to Etxeberria et al. [30], the new interfacial transition zone between the recycled aggregate and the cement paste was effective. It had a lower water/cement ratio than the adhered mortar present in recycled aggregate and the new cement paste (see Fig. 3). The ITZ is much denser than the old paste (adhered mortar) which is consequently weaker.

The recycled aggregate concretes had a larger splitting tensile strength than those of the control concretes, except for

the concrete where 100% of recycled aggregate was employed. However, in contrast, the modulus of elasticity of the recycled aggregate concretes was reduced when the recycled aggregates percentage was increased. This situation was expected, because recycled aggregates are more prone to deformation than raw aggregates. This finding is expected since recycled concrete aggregate has lower modulus than natural aggregate [14] and, in addition it is well known [31] that the modulus of concrete depends significantly on the modulus of the aggregates.

The test results of the modulus elasticity values of the different concretes were compared to the values calculated by the equations given by Ravindrarajah and Tam [17], according to the CEB-FIB recommendation [32], the method also defined by Ravindrarajah et al. [33], and according to Kakizaki [34], see Table 6 and Fig. 4.

According to the proposed Ravindrarajah and Tam model, when the percentage of the recycled aggregate was increased in the concrete the values were closer to the experimental values, so the model is quite valid with respect to recycled aggregate concretes. According to the CEB-FIB recommendation defined for conventional concretes, the E values for recycled aggregate and conventional concretes were overestimated. The proposed models by Ravindrarajah et al. [33] were not improved with respect to the method of Ravindrarajah and Tam [17]. Kakizaki's model for calculating the modulus of elasticity is acceptable for both conventional and recycled aggregate concrete.

3.4. Failure mode

The failure of the concrete derives from its weakest point. The weakest point being in these medium strength concretes, the recycled aggregates themselves. In medium strength conventional concretes, the interface is the weakest point however this is not the case when the concrete is made with recycled

Table 5
Properties of cylinder test specimens at 28 days and 6 months

	Compressive strength (MPa) 28 days	Compressive strength (MPa) 6 months	Tensile strength (MPa) 28 days	Tensile strength (MPa) 6 months	Modulus of elasticity (MPa) 28 days	Modulus of elasticity (MPa) 6 months
CC	35.53	42.54 (+19%)	2.84	3.64 (28%)	32,129	32,437
RC25	38.79	46.28 (19%)	3.01	3.88 (29%)	32,840	31,427
RC50	39.42	44.4 (13%)	3.36	3.65 (8.6%)	32,505	29,758
RC100	38.26	38.66 (1%)	2.79	3.28 (18%)	28,635	27,063

Concretes produce by automatic machine.

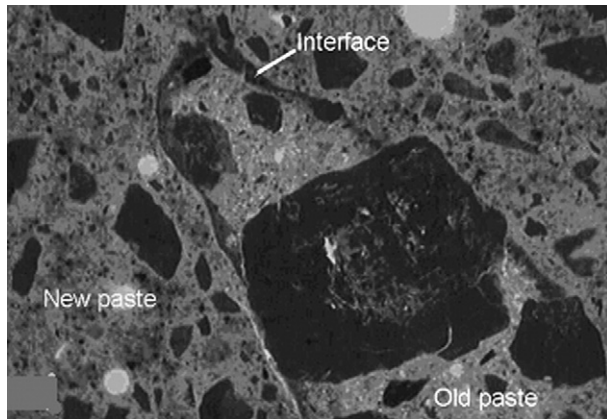


Fig. 3. Interface of recycled aggregate. The analysis was made by fluorescent thin section, Etxeberria M. et al. [30].

aggregates, as what happened in high strength concretes where the failure is through the aggregates. Fig. 5 shows splitting tensile failure of concrete made with a high amount of recycled aggregates. The failure happened through the recycled aggregates (the recycled aggregates being the weakest point) producing two similar symmetric faces, the failure never happened in the new interfacial transition zone. For low w/c ratios (old cement paste has a lower strength than the new one) the quality of the new paste is superior to the old paste. The strength of the new paste and that of the new mortar–aggregate bond are higher than the strength of the recycled mortar or that of the recycled mortar–aggregate bond thereby making the latter components the weakest and, therefore, the strength controlling links of the composite system [35]. When the water/cement ratio of the recycled concrete is lower than that of the original concrete, the strength of the recycled concrete may be controlled by the strength of the original concrete [36]. In this study, due to the high quality of the cement employed, the water/cement ratio used, the absorption capacity of the recycled aggregate, and the characteristics of the splitting failure (Fig. 6), the weakest point was the recycled aggregate and in particular the adhered mortar.

3.5. Variability of test result

In order to determine the variability of each concrete, the compressive strength was measured using a minimum of 20 test specimens for each concrete (in order to make the statistic value acceptable two concrete productions were used for RC25 and

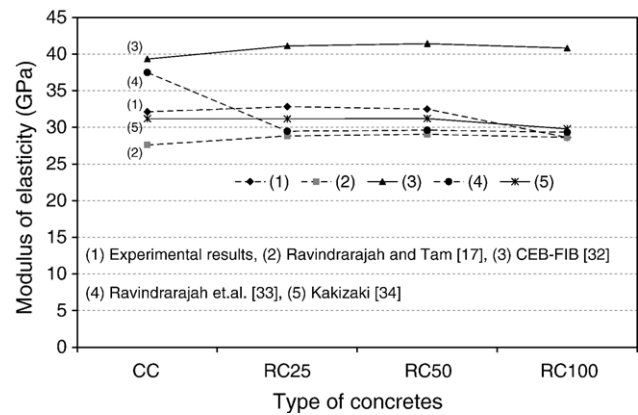


Fig. 4. Comparison of experimental modulus of elasticity values of four concretes (at 28 days) with analytical methods.

RC100 mixes). All the concretes were produced in a manual machine and the test cubic specimens were tested at 28 days of curing. On analysing the results, it was deduced that standard deviation of compressive strength increased with the increase of recycled aggregates in concrete. In this case, all the test elements had been cast in the laboratory so both their concrete components and their production was well controlled. The standard deviation increased by 18% and 49% in RC25 and RC100 concrete respectively in comparison with that of CC concrete due to the heterogeneous (different qualities) of the recycled aggregates. It is true, that the standard deviation value in all concretes was low (see Fig. 6). The recycled aggregate quality and concrete production control were high.

4. Conclusions

In accordance with the experimental phase carried out in this study, the conclusions obtained are with respect to;

4.1. The properties of recycled aggregates

Concrete crushed by an impact crusher achieves a high percentage of recycled coarse aggregates without adhered mortar.

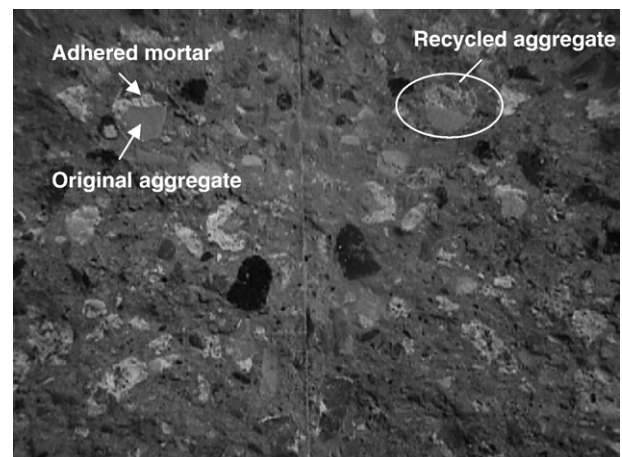


Fig. 5. Recycled aggregates concrete failure way by tensile.

Table 6
Different numerical methods to determine modulus of elasticity

Method	Modulus of elasticity
Ravindrarajah and Tam [17]	$E = 4.63f_{cy}^{0.50}$
CEB-FIB recommendation [32]	$E = 6.6f_{cy}^{0.5}$
Ravindrarajah [33]	$E = 5.31f_{cy}^{0.50} + 5.83$ for conventional concrete $E = 3.02f_{cy}^{0.50} + 10.67$ recycled concrete
Kakizaki [34]	$E_c = 2.1 * \left(\frac{d_s}{2.3}\right)^{1.5} * \left(\frac{f_c}{200}\right)^{0.5}$

Where: E : static modulus of elasticity, f_{cy} : compressive strength, d_s : density of concrete.

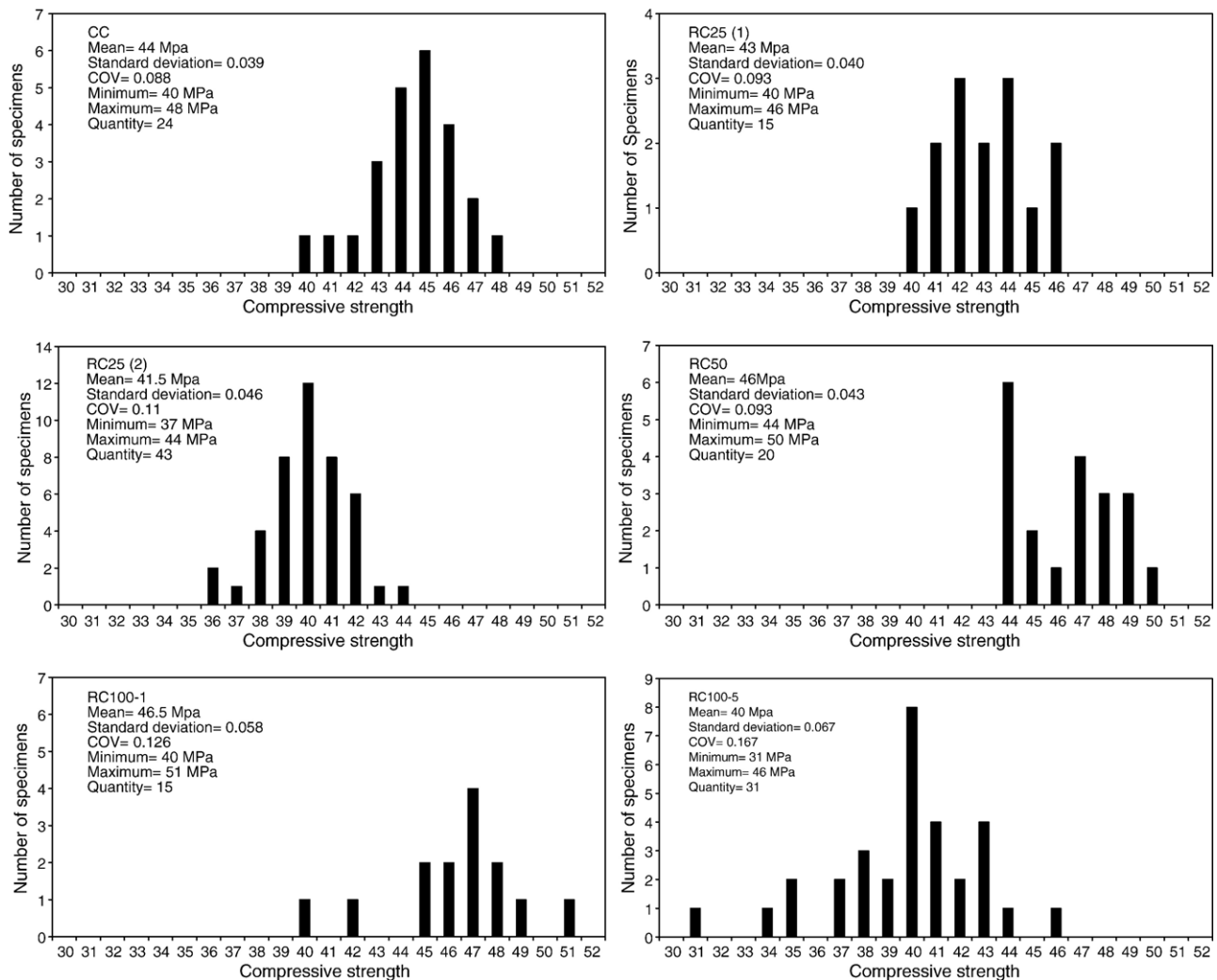


Fig. 6. Standard deviation of different type of concretes. RC100-1 and RC100-5: mix proportions of stage 1. CC; RC25 (1) and RC25 (2) the same mix proportions; and RC50: mix proportions of stage 2.

Their quality is acceptable according to physical properties for employing as secondary aggregates in concrete production.

The absorption capacity and the humidity level of recycled aggregates must be considered for concrete production. The humidity content in recycled coarse aggregates must be high. Consequently they should be used in concrete production with little absorption capacity in order to produce controlled quality concrete (the effective w/c ratio and fresh concrete workability).

4.2. Mechanical properties of recycled aggregate concrete

Concrete made with 100% of recycled coarse aggregates has 20–25% less compression strength than conventional concrete at 28 days, with the same effective w/c ratio ($w/c=0.50$) and cement quantity (325 kg of cement/m³).

Concrete made with 100% of coarse recycled aggregate requires high amount of cement to achieve a high compressive strength and consequently is not an economic proposition as it is not cost effective. These recycled aggregates should be used in concretes with low–medium compression strength (20–45 MPa).

Moreover, the adhered mortar in recycled aggregates is lower in strength than conventional aggregates and the new paste. Consequently the weakest point in concretes made with coarse recycled aggregates employing a cement paste of a medium–high strength (45–60 MPa) can be determined by the strength of the recycled aggregates or their adhered mortar.

Medium compression strength (30–45 MPa) concrete made with 25% of recycled coarse aggregates achieves the same mechanical properties as that of conventional concrete employing the same quantity of cement and the equal effective w/c ratio.

Medium compressive strength concrete made with 50% or 100% of recycled coarse aggregates needs 4–10% lower effective w/c ratio and 5–10% more cement than conventional concrete to achieve the same compression strength at 28 days. The modulus elasticity is lower than that of conventional concrete. However, the tensile strength of recycled aggregate concrete can be higher than that of conventional concrete (concrete using raw aggregates).

Standard deviation of compressive strength increases up to 50% employing a 100% recycled aggregate concrete mix than that of control concrete due to the heterogeneity of recycled aggregates.

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