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The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste

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ABSTRACT

Research on the use of Construction and Demolition Waste (CDW) as recycled aggregate (in particular crushed concrete) for the production of new concrete has by now established the feasibility of this environmentally-friendly use of otherwise harmful waste. However, contrary to conventional concrete (CC), no large applications of concrete made with recycled concrete have been made and there is still a lack of knowledge in some areas of production and performance of recycled aggregate concrete (RAC). One issue concerns curing conditions: these greatly affect the performance of concrete made on site and some potential users of RAC wonder how RAC is affected by far-from-ideal curing conditions.

This paper shows the main results of experiments to determine the influence of different curing conditions on the mechanical performance of concrete made with coarse recycled aggregate from crushed concrete. The properties analyzed include compressive strength, splitting tensile strength, modulus of elasticity, and abrasion resistance. The general conclusion in terms of mechanical performance is that RAC is affected by curing conditions roughly in the same way as CC.

1. Introduction

1.1. Preliminary remarks

The use of recycled aggregate (RA) in concrete opens a whole new range of possibilities for reusing materials in construction. Reuse of waste concrete as RA in new concrete is beneficial from the viewpoint of environmental protection and preservation of resources, as it reduces the use of non renewable materials used in concrete production and gives an alternate, and more environmentally-friendly, destination to this waste.

Earlier studies have mainly dealt with the processing of demolished concrete, mix proportion design, mechanical properties, durability aspects, and improvements [1,2]. Recently, the structural performance [3–5] and the economic aspects of using recycled aggregate concrete [6] have also been analysed and it has been proven that RAC can be considered a reliable structural material, given its particularities and if applied properly. Recent investigations on the performance of concrete made with recycled concrete fine aggregate [7–9] and recycled concrete coarse aggregate [10,11], and on the influence of the pre-saturation of recycled concrete coarse aggregate [12–14], have given positive results, which further support and encourage the possibilities of applying RAC in civil engineering structures.

As for the effect of the curing conditions on the performance of concrete, although it can be considered a subject of relatively minor importance for the performance of an average structure, due to its superficial impact on the cross-section of some of the structural elements [15], it is known to modify the mechanical behaviour of concrete, especially where tension forces are applied [16]. For some other structural elements were surface to volume ratio is high (e.g. slabs), the importance of the curing conditions on the hydration process of the cement constituents of concrete can be significant. This same issue can be considered of greater importance for RAC use, since the more porous structure of RAC allows greater water transfers between the elements and the environment and to a deeper extension. The main purpose of this investigation was to address whether RAC is more sensitive to adverse (or at least non-optimal) curing conditions than standard concrete.

Kou et al. [17] determined that the compressive strength of concrete seems to exhibit increasing indifference to steam curing conditions with the increase of the replacement ratio of natural coarse aggregate (NCA) by recycled coarse aggregates (RCA). This behaviour has been explained by the presence of free water inside the RCA which is released into the matrix as it is required. Similar results have been obtained for the modulus of elasticity, while some differences have been detected in studies on the tensile splitting strength. In another research [18], it has been determined that

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durability of RAC seems to benefit from extended wet curing conditions. Abrasion resistance depends greatly on the concrete's porosity and therefore it is expected that different curing conditions will affect this characteristic, since the surface moisture of concrete is completely different [19]. For all these reasons, it has been commonly assumed that RAC behaves differently if different curing conditions are taken.

1.2. Scope and methodology of the investigation

It is common knowledge that the mechanical behaviour of concrete depends on the characteristics of the aggregate, mix proportions and curing conditions, among other aspects (such as cement type, or its Blaine fineness) [20]. As investigations proceed on the use of RA in concrete production, there have already been several studies on the first two of these key factors but there is a lack of information about the influence of curing conditions on RAC properties.

This research aims to assess the influence of different curing conditions on the mechanical properties of recycled concrete coarse aggregate concrete (from herein referred as RAC, even though it concerns only coarse concrete aggregates), and to evaluate the effect of the incorporation of recycled concrete coarse aggregate (from herein referred as RCA, even though it concerns only the coarse fraction) on the properties of the concrete. Compressive strength, splitting tensile strength, the elasticity modulus and abrasion resistance are investigated. The test specimens were subjected to four types of curing conditions: laboratory conditions curing (LCC); outer environment curing (OEC); wet chamber curing (WCC); water immersion curing (WIC).

It is consensual in the scientific community that proper curing of concrete maintains a suitably warm (at least 5 °C, ideally over 10–15 °C) and moist environment for the development of hydration products, thereby reducing the porosity in hydrated cement paste and increasing the density of the concrete's microstructure. On the other hand, hot weather or low humidity curing may lead to micro-cracking due to drying shrinkage, which can jeopardize concrete's performance [20]. Neville [16] suggest that a relative humidity above 80% should be kept, if proper cement hydration is to be achieved. If a concrete is not well cured, particularly at an early age, it can suffer irreparable loss, as it will not gain the targeted properties due to a lower degree of hydration [21], or because of the detrimental effects that drying and possibly autogeneous shrinkage, especially for concrete with lower *w*/*c* ratios, can have on its performance.

In order to determine the effect of different curing conditions on the mechanical performance of RAC, four families of concrete made with increasing replacement ratios of NCA by RCA were subject to different curing conditions, ranging from laboratory controlled to weather exposed. Comparisons between the performance variations measured within each family were made, as well as the analysis of the influence of the curing conditions for each level of replacement.

2. Experimental program

Four concrete mixes were produced using different replacement ratios, along with four different curing methods. To compare different mixes and/or curing conditions, and guarantee they will have approximately the same end-uses, the concrete mixes were designed so they would have the same workability, thus also eliminating this entropic parameter from the analysis. After the curing period, hardened concrete tests were performed.

Experimental results were then analyzed and discussed in detail. Correlations were established between the properties of the RAC and the density and water absorption of the aggregate, the replacement rate of NCA by RCA, and the curing conditions as well.

2.1. Materials and mix design

Four different concrete mixes were produced: a conventional reference concrete (NAC) and three recycled aggregate concretes (RAC) with replacement rates of 20%, 50% and 100% of NCA by RCA. All concrete mixes (NAC and RAC) were prepared based on an effective water/cement ratio of 0.43 and were balanced to have a slump of 80 ± 10 mm (as measured with the Abrams cone).

The coarse recycled concrete aggregate was obtained by crushing a laboratory produced primary concrete, using a jaw crusher. The use of laboratory produced concrete allows control of its production and it can then be characterized thoroughly. The main properties of the primary concrete are presented in Table 1.

The proportions of the materials were determined on the basis of the absolute volume of the constituents: CEM II A-L 42.5R cement, natural limestone coarse aggregates, river sand and tap water. Table 2 presents the main physical properties of the natural and the recycled aggregates, while Table 3 presents the mix proportions of all concrete mixes analysed. The coarse aggregates were totally separated by sieve sizes. This was made for the NCA, to allow a perfect match of the theoretical grading curve defined by the Faury method. In the case of the RCA, this procedure was adopted to match the grading curves of the RCA and NCA, eliminating entropies in the interpretation of the variability measured in the tests. The amount of water added correspond is an absolute value, considering the extra water required for the RCA's absorption. The relationship between total amount of water and cement is referred as "apparent water/cement ratio", whereas the relationship between amount of water used in the hydration process and cement is referred as "effective water/cement ratio". The effective water/cement ratio presented shows that the incorporation of RCA in the mixes has no direct influence on the workability of concrete.

2.2. Curing conditions

Regular tap water was used in WIC and the curing temperature was maintained at 16.3 °C. The WCC specimens were kept at a relative humidity of 100% and 20.0 °C temperature. In the case of OEC, the specimens were exposed to the weather without any kind of protection and were continuously monitored with a thermo-hygrometer. Testing took place between November 2007 and May 2008, corresponding to Mediterranean winter/spring conditions. The LCC specimens were preserved in laboratory (non-standard humidity and temperature conditions), but protected from harsh weather changes.

It should be noted, by comparison with the literature review above, that most of these curing conditions have never been systematically/extensively analyzed within the scope of RAC.

Table 1
Properties of primary concrete.

Coarse aggregate 1	552
Coarse aggregate 2	338
Coarse aggregate 3	188
Fine sand	269
Coarse sand	445
CEM II A-L 42.5R cement	360
Water	190
Water/cement ratio	0.53
Maximum aggregate size (mm)	25
Slump (mm)	90
f_{cm} at 28 days (MPa)	39.6

Table 2
Main physical properties of the natural and the recycled aggregates.

Aggregates	Fine sand	Coarse sand	Granule	Fine gravel	Coarse gravel	RCA
Oven dry density (kg/dm^3)	2.59	2.54	2.56	2.57	2.51	2.31
Saturated surface-dry density (kg/dm^3)	2.60	2.56	2.60	2.61	2.55	2.45
Water absorption at 24 h (%)	0.4	0.5	1.7	1.5	1.3	6.1
Bulk density (kg/dm^3)	1.41	1.52	1.42	1.44	1.46	1.17
Los Angeles wear test (%)	–	–	28.3	29.4	30.7	42.7
Shape index (%)	–	–	8.6	13.4	11.1	24.3
Water content (%)	0	0	0.6	0.6	0.6	4.1

Table 3
Compositions of all concrete mixes.

Component		Quantities (kg/m^3)			
		RC	C20	C50	C100
Coarse natural aggregates	4–5.6 mm	103.7	83.0	51.9	–
	5.6–8 mm	117.8	94.3	58.9	–
	8–11.2 mm	119.1	95.3	59.6	–
	11.2–16 mm	236.8	189.4	118.4	–
	16–22.4 mm	293.3	234.6	146.6	–
	22.4–25.4 mm	114.7	91.8	57.4	–
Coarse recycled aggregates	4–5.6 mm	–	19.5	48.9	97.7
	5.6–8 mm	–	22.2	55.5	111.0
	8–11.2 mm	–	22.5	56.1	112.3
	11.2–16 mm	–	44.6	111.6	223.1
	16–22.4 mm	–	55.3	138.2	276.4
	22.4–25.4 mm	–	21.6	54.0	108.1
Fine sand		167.0	167.0	167.0	167.0
Coarse sand		528.6	528.6	528.6	528.6
CEM II A-L 42.5R cement		446	446	446	446
Water		191.6	191.6	194.4	198.7
Apparent water/cement ratio		0.43	0.43	0.44	0.45
Effective water/cement ratio		0.43	0.43	0.43	0.43
Slump (mm)		97	86	87	87

RC – reference concrete (without recycled aggregates); Cxx – concrete with xx% replacement in volume of natural coarse aggregates with recycled coarse aggregates.

Furthermore, real far-from-ideal curing conditions (LCC and OEC) are reproduced in RAC for the first time.

2.3. Testing procedures

The aggregate's main properties were studied according to the most recent European standards. Water absorption of the RAC over time was determined following the methodology established by Ferreira et al. [13]. This methodology allows taking into account in the determination of the mixing water content that RCA have much higher water absorption than NCA. The test procedure consists in determining the evolution of water absorbed by a immersed RCA sample, previously oven dried, by means of an hydrostatic balance. In order for the various mixes to have the same effective water/cement ratio (i.e. the same free water for cement hydration and flowability purposes), the extra amount of water that RCA absorb during mixing was added to the mixer. Fig. 1 shows the evolution of water absorption over time. It is during the first 5 min that most of the water absorption occurs. Accordingly, it was considered that 90% of the maximum absorption potential occurred after 5 min and this amount of water was added to the mix deducted of the water content in the aggregates (measured before the mix).

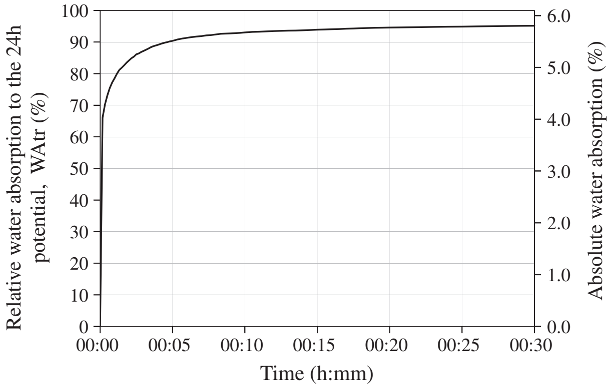

Fig. 1. Water absorption evolution of the RCA.

The same hardened concrete tests were performed on all compositions. Compressive strength was measured according to EN 12390-3 [22] at the age of 7, 28 and 56 days on 0.15 m cubic specimens (3, 5 and 3, respectively). 28-days tensile splitting strength was measured following EN 12390-6 [23] on three cylindrical specimens. Elasticity modulus in compression was measured following LNEC E-397 [24] on two cylindrical specimens. Abrasion resistance was determined by Böhme's grinding wheel wear test, according to DIN 52108 [25], using three $71 \times 71 \times 50\ \text{mm}^3$ specimens.

3. Results and discussion

3.1. Compressive strength

The compressive strength results (both mean values – f_{cm} – and standard deviations – SD) for all curing conditions and replacement ratios (defined by the general designation of C**, where ** stands for the replacement ratio as a percentage) are given in Table

Table 4
Compressive strength of the different compositions under different curing conditions (MPa).

Curing condition	Age (days)		CC	C20	C50	C100
LCC	7	f_{cm}	42.2	42.7	42.5	45.6
		SD	1.43	1.46	0.84	1.43
	28	f_{cm}	51.0	48.8	51.3	51.2
		SD	1.31	1.07	3.28	1.36
	56	f_{cm}	53.4	53.5	51.7	54.4
		SD	1.83	1.98	0.93	2.21
OEC	7	f_{cm}	42.9	39.5	41.6	41.8
		SD	0.14	1.83	1.11	0.10
	28	f_{cm}	51.7	50.6	50.3	49.2
		SD	1.99	2.30	1.02	0.50
	56	f_{cm}	50.0	50.9	52.0	49.1
		SD	3.11	3.24	0.95	0.43
WCC	7	f_{cm}	44.5	43.2	42.1	42.9
		SD	2.59	0.68	0.90	0.63
	28	f_{cm}	48.8	48.0	47.7	47.2
		SD	2.33	1.45	1.63	2.40
	56	f_{cm}	49.3	48.4	52.0	51.4
		SD	1.97	0.43	2.83	2.10
WIC	7	f_{cm}	44.6	43.9	44.0	43.0
		SD	3.20	0.71	1.21	0.60
	28	f_{cm}	50.5	50.1	48.8	50.0
		SD	2.10	3.98	1.51	1.45
	56	f_{cm}	53.7	52.6	51.0	53.3
		SD	1.58	0.79	1.87	1.77

LCC – laboratory curing; OEC – outer environment curing; WCC – wet chamber curing; WIC – water immersion curing; RC – reference concrete (without recycled aggregates); Cxx – concrete with xx% replacement in volume of natural coarse aggregates with recycled coarse aggregates.

4. Figs. 2–4 give the relationship between compressive strength of RAC and NAC, given the age of the specimens and their curing conditions.

With all curing methods, the concrete's compressive strength increased with age. The average of the compressive strength (f_{cm}) at 7, 28 and 56 days is respectively 42.8, 49.8 and 51.6 MPa. Generally speaking, after 7 and 28 days of curing the specimens exhibited about 80% and 95%, respectively, of their 56-days compressive strength.

It was expected that compressive strength would decrease linearly with the replacement of NCA by RCA [10]. In fact, the difference between the compressive strength of all the different concrete mixes is equal or less than 7.5% in relation to the NAC's. There are two possible reasons for this: one is that the RCA adhered paste contains un-hydrated cement that contributes to strength gains [26]; the other is the increased roughness and specific surface of the RCA that contributes to a better interconnection between the recycled aggregates and the new cement paste than for the reference concrete [27]. Therefore, no distinct relationship can be established between the compressive strength and the proportion of RA in the concrete mix. For the same reason RAC seem to be equally affected by curing conditions as NAC.

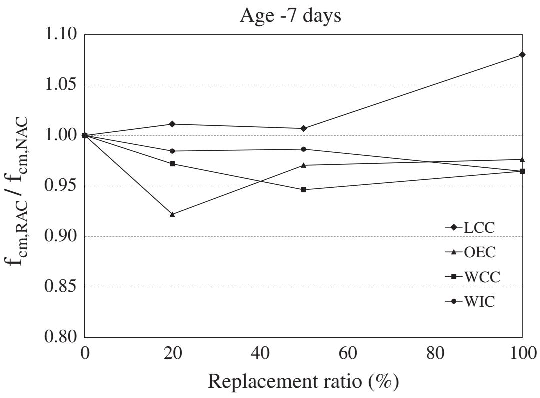

Fig. 2. Relative compressive strength of RAC and NAC (for different curing conditions at 7 days) *versus* replacement ratio of CNA by CRA.

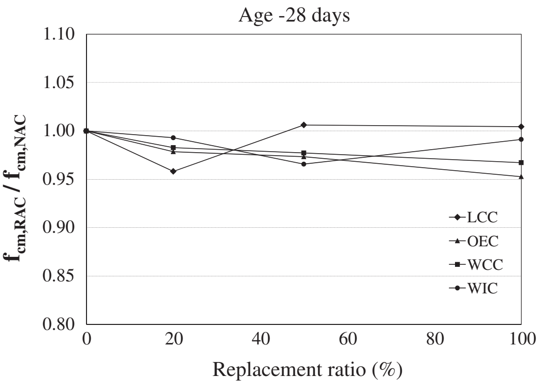

Fig. 3. Relative compressive strength of RAC and NAC (for different curing conditions at 28 days) *versus* replacement ratio of CNA by CRA.

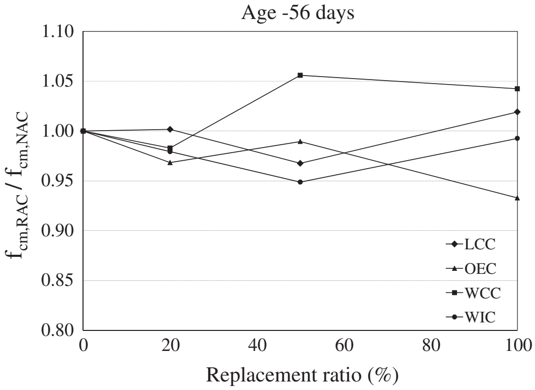

Fig. 4. Relative compressive strength of RAC and NAC (for different curing conditions at 56 days) *versus* replacement ratio of CNA by CRA.

The optimal design of the mixes, accounting for water absorption of CRA and the use of a pre-saturation process, which allow a better control of the effective water/cement ratios, seems to have a major effect on the results. The results show that the properties of the RCA are similar to those of the concrete's cement matrix and are thus not a weak point. These similar values of compressive strength for RAC can be explained by the higher porosity and roughness of the RCA, which enables a better mechanical bonding between the cement matrix and the RCA, thus offsetting their lesser strength [28,29].

Figs. 5–8 show the effects of the different curing conditions on the development of compressive strength with age, for each of the families of concrete tested. Generally, OEC seems to lead to compressive strength stabilization after the 28th day of curing but concrete C50 does not follow this trend and shows a slight increase in compressive strength after the 28th day. Similar behaviour is noted for WCC conditions for mixes CC and C20. Otherwise the concretes' compressive strength increases over time, as expected.

The compressive strength results are in disagreement with those previously obtained for analogous investigations. Whereas Kou et al. [17] established that compressive strength is affected by the replacement ratio of NCA by RCA, in the current research similar strength was measured for the complete range of replacement ratios tested. Also, these authors state that compressive

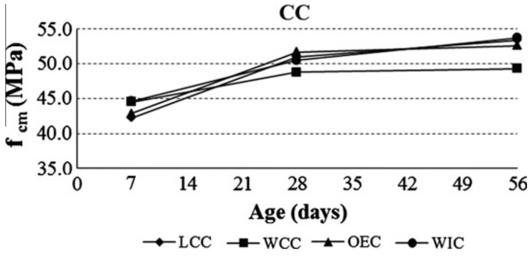

Fig. 5. Compressive strength *versus* time for the reference concrete (CC), for different curing conditions.

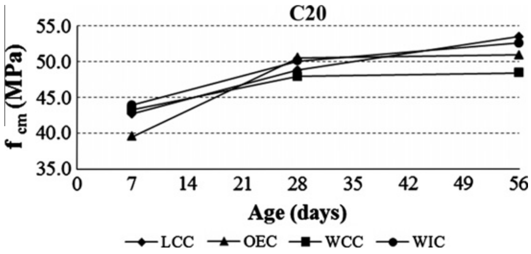

Fig. 6. Compressive strength *versus* time for concrete with 20% replacement of NCA by RCA (C20), for different curing conditions.

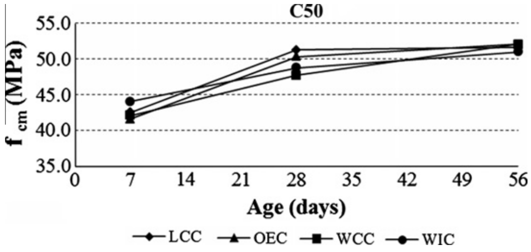

Fig. 7. Compressive strength *versus* time for concrete with 50% replacement of NCA by RCA (C50), for different curing conditions.

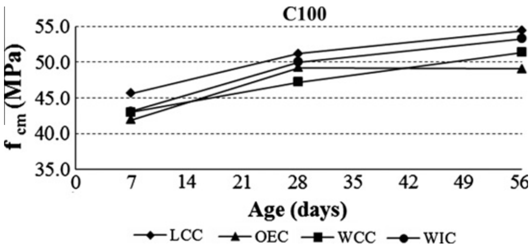

Fig. 8. Compressive strength *versus* time for concrete with 100% replacement of NCA by RCA (C100), for different curing conditions.

strength seems to be affected by the curing conditions, for different replacement ratios, which was not the case in the present study. The possible reasons for these discrepancies were stated above.

3.2. Splitting tensile strength

Results of the 28-days splitting tensile strength of all concrete mixes are presented in Fig. 9. Generally, the 28-days splitting tensile strength decreased with the increased incorporation of RCA and it ranged from 2.37 to 3.88 MPa for different RCA incorporation percentages and curing methods. All C100 typologies exhibit lower values for splitting tensile strength, with the exception of WCC specimens which reveal a slightly higher value than NAC-WCC. Table 5 shows the ratios between tensile strength and compressive strength at 28 days for the different curing conditions. Although the values are somewhat similar, there is no visible trend that can be easily correlated to the replacement ratio or type of curing condition.

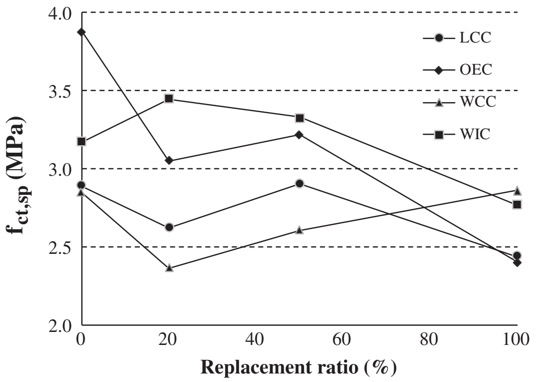

Fig. 9. Splitting tensile strength *versus* replacement ratio of NCA by RCA, for different curing conditions.

RAC specimens kept in OEC conditions appear to be more susceptible to this curing method than regular concrete. LCC and WIC curing methods exhibit a similar development with increasing incorporation of RCA, and so they do not seem to affect RAC more, or less, than CC. On the other hand, WCC specimens reveal an unexpected variation, with splitting tensile strength increasing when the NCA is replaced by RCA. As other studies have found [18], the curing conditions seem to affect the performance of RAC, although it is not clear to what extent in numerical terms. Nevertheless, WIC and OEC consistently exhibit higher tensile strengths than LCC and WCC with up to 50% replacement ratio, while at 100% replacement ratio those values are closer, with WCC and WIC showing the better results.

3.3. Elasticity modulus

Results of the elasticity modulus in compression of all concrete mixes are presented in Fig. 10. The modulus of elasticity decreased as the incorporation of RCA increased and it varied from 30.6 to 43.4 GPa, for different RCA incorporation ratios and curing methods.

LCC specimens display the lowest elasticity modulus values (Fig. 10). Concrete's modulus of elasticity is known to be highly dependent on the stiffness phases (the aggregates, the cement paste and the interfacial transition zone – ITZ) [30]. One of the major factors that regulates the stiffness of the aggregate and cement paste phases is their porosity and therefore it is natural that as the replacement ratio of NAC by RAC increases so the modulus of elasticity decreases. On the other hand, the low humidity condition of LCC potentiates the development of a more porous cement paste, which in turn will cause the modulus of elasticity to be lower than for the other curing conditions. The remaining curing conditions have fairly similar modulus of elasticity values, although the trend seems to point to a decreasing modulus of elasticity as the environ-

Table 5
Ratio of tensile strength to compressive strength (MPa).

	OEC	LCC	WCC	WIC
CC	0.075	0.057	0.058	0.063
C20	0.060	0.054	0.049	0.069
C50	0.064	0.057	0.055	0.068
C100	0.049	0.048	0.061	0.055

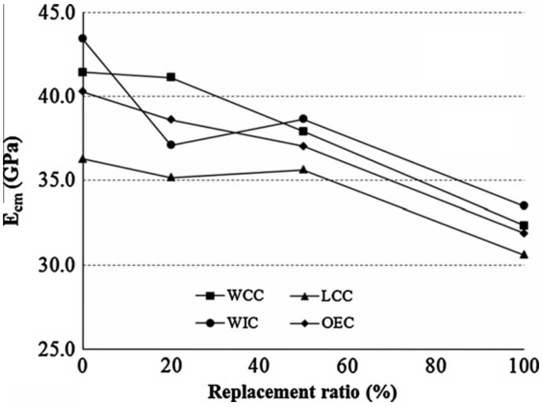

Fig. 10. Modulus of elasticity *versus* replacement ratio of NCA by RCA, for different curing conditions.

ment moisture content decreases (with WIC the highest and OEC the lowest).

Regarding the modulus of elasticity, given the curing condition, the variation of the LCC specimens' elasticity modulus (Fig. 10) suggests that the incorporation of RCA in RAC leads to fewer effects in these curing conditions than in others (incorporation of RCA still leads to lower values, but at a less significant rate). The phenomenon may be explained by the fact that the cement paste phase of the LCC concrete mixes is weaker (no matter how much RCA is present) and therefore directly influences the final result. The other curing conditions (OEC, WCC and WIC) all included high relative humidity and exhibit very similar correlations with RCA incorporation. For the same reason, RAC do not seem to be particularly affected by curing conditions compared with CC.

Regardless of the influence of the curing conditions on the modulus of elasticity of RCAC, these findings are higher than or within the range of some recent studies [31,32], indicating that the concrete mixes tested are suitable for use in concrete structures.

3.4. Abrasion resistance

Results of the abrasion resistance of all concrete mixes are presented in Fig. 11. Since curing conditions strongly affect concrete's surface layer, note that the test specimens ($71 \times 71 \times 50\ \text{mm}^3$) were obtained by sawing larger concrete cubes (100 mm edge) after curing so that the concrete's surface finishing would not be a variable in the test. Thus, the test surface is the cutting surface itself, i.e. an internal plane of the concrete element, composed of aggregate and cement mix, and not an outer surface.

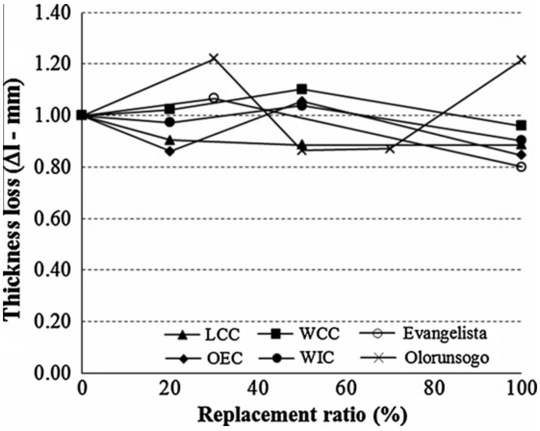

Fig. 11. Thickness loss due to abrasion *versus* replacement ratio of NCA by RCA, for different curing conditions.

The inconsistent variation of abrasion resistance values, in all curing conditions, means that a clear relationship between this property and the incorporation of RCA cannot be established. Apart from the C50-WCC mix, which exhibits 10% higher wear than the NAC mix, the abrasion resistance of all other concrete' types differs by no more than 5.4% in relation to NAC, which is not statistically significant from an experimental point of view.

The C100 specimens show the lowest loss of thickness and subsequently higher abrasion resistance, for all curing conditions thus enabling to conclude that incorporating RCA leads to better performance in terms of abrasion resistance. This can be explained by the better bond established between the cement and RCA because of the latter's higher porosity [33].

No clear conclusions can be reached with respect to curing conditions, but the lower variations suggest that RAC do not appear to be affected any differently from CC. The results indicate that the performance of mixes incorporating RA is comparable to the concrete mix in which 100% NCA was used.

In order to benchmark the results achieved, abrasion resistance tests on concretes made with recycled aggregates from two other studies (Evangelista and de Brito [7] and Olorunsogo [34]) are also presented; they show similar behaviour to that observed in the current research.

4. Conclusions

It is common knowledge that recycled aggregates concrete (RAC) are expected to have poorer performance than conventional concrete (CC). Nevertheless, this type of concrete can still be suitable for use as a structural material. The following conclusions can be drawn based on the experimental results and the respective discussion of the study:

- Compressive strength does not seem to be affected by recycled concrete coarse aggregate (RCA) incorporation for a given curing condition, compared to CC; also, compressive strength (both for CC and RCA) seems to be reasonably insensitive to curing conditions, for a given replacement ratio; the differences between this and other investigations may have to do with the pre-wetting process used that stabilizes the effective w/c ratio in all mixes.
- Splitting tensile strength decreases with the increased RCA incorporation; RAC specimens in outer environment curing (OEC) conditions seem to be more susceptible (i.e. the difference between the splitting tensile strength of CC and that of the various RCA mixes is bigger) to these curing conditions than CC specimens.
- Elasticity modulus decreases with the increased RCA incorporation but RAC specimens in laboratory conditions curing (LCC) seem to be slightly less affected by RCA incorporation. The elasticity modulus of RAC in the other curing conditions (OEC, wet chamber curing (WCC), and water immersion curing (WIC)) does not seem to be more, or less, affected than that of CC.
- Abrasion resistance test values vary inconsistently and so no correlation can be established but the low variations suggest that the performance of mixes incorporating RA is comparable to that of CC, regardless of the curing conditions. However, it is noticed all RAC100 mixes exhibit the lowest wear of all mixes for the same curing conditions.

This field presents many research possibilities (and necessities) if the behaviour of recycled aggregate concrete is to be fully understood. Nevertheless this experimental study emphasizes that this type of aggregate has potential as a component in the production of structural concrete, as other investigations have proved regarding other aspects. This research presents arguments that tend to contradict a common assumption that recycled aggregate concrete is more sensitive to different curing conditions and therefore removes another obstacle to its massive use.

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