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Anchorage of steel rebars to recycled aggregates concrete

M. Guerra [a], F. Ceia [a], J. de Brito [b,*], E. Júlio [b]

[a] Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[b] ICIST, DECivil, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

HIGHLIGHTS

- Concrete made with coarse recycled concrete aggregates.
- Anchorage strength of ribbed steel rebars with varying length and diameter.
- The anchorage strength decreases with the incorporation ratio of recycled aggregates.
- Numerical modelling of the experimental tests.

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ABSTRACT

This research aims at evaluating the effect of the replacement ratio of natural course aggregates (NCA) by recycled concrete coarse aggregates (RCCA) on the anchorage strength of ribbed steel rebars to concrete.

To accomplish this purpose, four concrete mixes were designed: a conventional NCA concrete (NCA by RCCA replacement ratio of 0%) to serve as reference and three recycled aggregates concrete (RAC) with 20%, 50% and 100% NCA by RCCA replacement ratios. Besides this parameter, all the remaining ones were kept constant. An effective water/cement ratio of 0.53 and a slump of 125 ± 10 mm were adopted.

The mechanical properties of the considered mixes were characterized in terms of compressive strength, splitting tensile strength, and Young's modulus. The anchorage strength of ribbed steel rebars to RAC was assessed for each of the four concrete mixes using pull-out tests. In addition to the NCA by RCCA replacement ratio, two other variables were evaluated: the diameter (12 and 16 mm) and the anchorage length (5ϕ, 10ϕ and 15ϕ) of the steel rebars. The combination of these three variables led to 24 different testing conditions. For each of these, three equal specimens were produced, corresponding to a total of 72 pull-out tests performed.

As main conclusions of this research study, it can be stated that NCA by RCCA replacement ratio has a negative impact on the mechanical properties of concrete, presenting an approximately linear correlation. Only for lower replacement ratios, namely 20%, there are not any clear changes in concrete mechanical properties, and a slight increase can even occur. Regarding the anchorage strength of ribbed steel rebars to concrete, the incorporation of RCCA has a similar effect: the increase of the NCA by RCCA replacement ratio leads to a decrease of this parameter. This effect can be well explained analysing the stress distribution inside the pull-out specimens using a finite-element model developed with this aim, also presented herein.

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1. Introduction

1.1. Initial remarks

Construction represents an important pillar of most countries economy. The natural resources used by this sector are extracted from Nature at an extremely high rate, when compared to the one at which they are restored, being thus unsustainable. In what concerns the extraction of natural stone for construction, 90% of this activity within the European Union is concentrated in only five countries: Portugal, Spain, Greece, Italy and France [1]. Moreover, since these natural resources are available at low costs in these countries, the recycling rates of construction and demolition waste (CDW) are only marginal (less than 5%), significantly lower than the overall figure of 46% in the European Union [2]. Given the present scenario, all studies leading to use recycled aggregates concrete (RAC) in both new and existing structures is absolutely mandatory.

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[*] Corresponding author. Tel.: +351 218419709; fax: +351 218497650.
E-mail address: jb@civil.ist.utl.pt (J. de Brito).

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However, most studies only deal with the material characteristics of RAC and do not address structural RAC.

1.2. Research significance

The main objective of the research study herein described is to characterize the influence of replacing natural course aggregates (NCA) by recycled concrete coarse aggregates (RCCA) on the anchorage of ribbed steel rebars, thus contributing to the use of structural RAC.

In this research study, except for the NCA by RCCA replacement ratio, all parameters of the adopted RCCA concrete mixes were kept constant, namely: cement dosage, aggregates' size distribution, and workability of concrete in the fresh state (calibrating the w/c ratio to take into account the higher permeability of RCCA relatively to NAC). Besides the NCA by RCCA replacement ratio, the influence of steel rebars' diameter and anchorage length was also investigated. In addition, numerical models were also considered to simulate pull-out tests, thus allowing in depth analysis of the stress distribution at the rebar-to-concrete interface before sliding.

The main conclusion, and innovative contribution of this study, is that regarding anchorage of ribbed steel rebars in RAC, it can be stated that, below a 50% NAC by RCCA replacement ratio, this type of RAC can be used in structures without any type of design and/or detailing specification change.

2. Literature review

In this section, a synthesis is made of the state of the art on the fields of knowledge relevant for this research study, namely recycled aggregates concrete and bonding between steel rebars and concrete.

Concerning the RCCA's properties, Matias et al. [3] highlight the influence of the cement paste bonded to the surface of the original natural aggregates, corroborating the study by Gonçalves and Neves [4] who stated that the optimization of both the size distribution and the shape of particles is achieved when the incorporated CDW is processed by primary and secondary crushing, allowing the effective removal of the most fragile parts of their mass. Matias et al. [3] also mention that the cementitious paste gives the recycled concrete aggregates (RCA) a rougher, lighter and more porous structure, thus decreasing their particles' density and increasing their water absorption.

The RCA's characteristics, and particularly those of the RCCA, influence the properties of the concrete in which they are incorporated. The density of recycled concrete coarse aggregates concrete (RCCAC) is lower than that of the corresponding reference concrete (RC) (i.e. same composition but with NCA instead of RCCA), due to the lower density of RCCA. According to Kou and Poon [5], the incorporation of RCA decreases the mechanical properties of concrete (at 28 days), in particular the compressive strength, the splitting tensile strength and the Young's modulus. In this study [5], the loss of strength proved to be proportional to the replacement ratio of NCA by RCCA. The authors also showed that the differences in strength between RCCAC and RC decreased for longer curing ages. Fonseca et al. [6] studied the incorporation of RCCA in structural concrete and concluded that the splitting tensile strength is more sensitive to the replacement of NCA by RCCA than the compressive strength (at 28 days). In this study [6], the Young's modulus was also negatively affected by the RCCA incorporation. According to Coutinho and Gonçalves [7], the relationship between the Young's modulus of concrete and of its aggregates is different from that between the corresponding values for the compressive strength or the splitting tensile strength, because the former is mostly conditioned by the aggregates' stiffness, while the remaining depend mostly on the aggregates' mechanical strength. For this reason, since RCCA have lower stiffness than NCA, due to the bonded cement paste, the Young's modulus is expected to be closely related with the replacement ratio of NCA by RCCA, as Fonseca et al. [6] showed.

Some authors like Evangelista and de Brito [8] and Gomes and de Brito [9] obtained slight increases in strength in concrete incorporating recycled concrete fine aggregates (RCFA) and RCCA, respectively, justified by the presence of non-hydrated cement particles in the recycled aggregates that increased the absolute cement content in the mixes.

Regarding bonding of steel rebars to RCCAC, only few studies are published [10–12]. Furthermore, both results and conclusions are not consensual. This is one of the motivations for the study herein presented.

Xiao and Falkner [10] studied the bond of steel rebars to non-structural RCCAC. Ribbed steel rebars were used with a diameter of 10 mm. Three concrete mixes were adopted with the following NCA by RCCA replacement ratios: 0%, 5% and 100%. RCCA were pre-saturated in order to eliminate the influence of their higher water absorption capacity, thus allowing the effective water/cement ratio of all mixes to remain constant and equal to 0.43. Bond between steel rebars and RCCA was assessed using pull-out tests. This study [10] presented similar values of the bond stresses, independently of the replacement ratio of NCA by RCCA, contrarily of the compressive strength which values decreased proportionally to the replacement ratio. The authors concluded that, for reinforced RCCAC structures, the considered anchorage length can be the same as in conventional NCA concrete.

Kim and Yun [11] also conducted pull-out tests to study the bond between ribbed steel rebars with a diameter of 16 mm and RCCAC. The adopted RCCA resulted from processing CDW from a building demolition. Besides the replacement ratio of NCA by RCCA (0%, 30%, 60% and 100%), the authors also studied the effect of: (i) the maximum aggregates' size (20 mm and 25 mm), (ii) the direction of casting relatively to the steel rebars (parallel or perpendicular), and (iii) the distance of the steel rebars to the specimen's bottom.

For the specimens cast parallel to the steel rebars (as in the present study), the results showed different trends according to the maximum aggregates' size. The bond stress was higher in the specimens with smaller maximum aggregates' size (D_{max}) and it did not change significantly with the increase of the NCA by RCCA replacement ratio. Conversely, the bond stress of the specimens with higher D_{max} was negatively affected by the RCCA incorporation. In both concrete mixes, the compressive strength (at 28-days of age) dropped proportionally to the RCCA's incorporation ratio.

Butler et al. [12] also studied the influence of the incorporation of RCCA in concrete on the bond of (25.2 mm diameter) steel rebars to concrete. Beam-end tests were used aiming at simulating the pull out of steel rebars from current reinforced concrete elements, i.e. containing stirrups and longitudinal reinforcement. The authors studied the influence of the following three parameters: (i) the RCCA type, by selecting two sources of aggregates; (ii) the anchorage length (125 mm and 375 mm) of the steel rebar subjected to the pull-out force; and (iii) the concrete compressive strength (30 MPa and 50 MPa). The RCCA were subjected to several physical–chemical processes to remove the cement paste.

In this study [12] it is concluded that the incorporation of RCCA affects negatively the bond between steel rebars and concrete, even if the latter is produced to have the same compressive strength as the RC. According to Butler et al. [10], there is a weak correlation between the bond stress and the splitting tensile strength of concrete. On the other hand, the proposed correlation between the bond stress and the crushing resistance of RCCA adjusted well to measured values, highlighting the importance of knowing both the source and the characteristics of these aggregates. Relatively to the influence of the anchorage length, results were inconclusive.

3. Experimental program

The experimental campaign was organized in five stages: (i) RCCAC mix design, (ii) aggregates characterization tests, (iii) fresh-state concrete tests, (iv) specimens' production and hardened-state concrete tests, and (v) pull-out tests.

At the first stage, four concrete mixes were designed, corresponding to four replacement ratios of NCA by RCCA: 0%, 20%, 50% and 100%, corresponding the first to the reference concrete (RC) and the last to total replacement of NCA by RCCA. The 50% ratio was adopted for being the intermediate point. And the 20% ratio was included because it is considered in some standards [13] as the acceptable limit ratio for the incorporation of recycled aggregates in structural concrete. In order to reduce the entropy of the experimental programme, both the size distribution of aggregates and the workability of concrete in the fresh state were kept constant in all concrete mixes.

At the second stage, all the aggregates necessary for the experimental campaign were carefully calibrated. Natural fine aggregates (NFA) were adopted in all mixes, i.e. no recycled fine aggregates were used. To obtain the RCCA, a source concrete (SC) was first produced, adopting the same characteristics of the RC (C30/37 strength class, S3 consistency class, $D_{\max} = 22.4$ mm). These three properties were chosen according to the experimental campaigns found during the literature review within the same research scope as our paper so that the results could be more easily compared. Then the SC was crushed and sieved, using the same procedure adopted for the NCA. The SC and the NCA were supplied by the same company, in order to guarantee that the NCA used in both the SC and in the RCCAC produced in the experimental campaign were the same.

The characterization of the aggregates was made using the following tests and corresponding standards: sieve analysis (EN 933-1) [14], particles' density and water absorption (EN 1097-6) [15], apparent bulk density (EN 1097-3) [16], water content (EN 1097-5) [17], Los Angeles wear (LNEC E-237) [18], and shape index (EN 933-4) [19].

At the third stage, the concrete mixes designed at the first stage were characterized in the fresh state. An effective water/cement ratio of 0.52 was adopted for all mixes, after compensating the higher water absorption of the RCCA, following the procedure defined by Ferreira et al. [20]. According to the latter, the determination of the extra water is based on: (i) the water absorption of the RCCA after 10 min (3.18%), (ii) the estimated mixing time, and (iii) the weight of the RCCA incorporated in each mix. Table 1 presents the composition of each of the four concrete mixes adopted in this study.

The slump test (EN 12350-2) [21] confirmed that the mixtures presented the same workability. The fresh-state density test was also performed for each mix (EN 12350-6) [22].

At the fourth stage, all specimens were produced and the following characterization tests of concrete in the hardened were performed, according to the corresponding standards: compressive strength (EN 12390-3) [23], splitting tensile strength (EN 12390-6) [24], and Young's modulus (LNEC-397) [25].

Finally, at the fifth stage, the pull-out tests were performed to study the anchorage of steel rebars to RCCAC, the ultimate goal of the study herein presented. The testing setup adopted by Jorge et al. [26] was used, also taking into account guidelines by RILEM/CEB-FIP [27]. The choice of this procedure is mostly related with the shape and size of the specimens. Cylindrical specimens were adopted instead of cubic specimens, most common in the literature, to provide an axisymmetric cover and confinement of the steel rebars, thus preventing the effect of other parameters besides those under analysis.

Fig. 1. Pull-out test specimens.

The following geometry was adopted for pull-out specimens: a 200 mm diameter and 300 mm height concrete bulk, and 12 mm and 16 mm ribbed steel rebars embedded in the latter with an anchorage length proportional to their diameter (ϕ): 5ϕ, 10ϕ and 15ϕ. The needed free length of the ribbed steel rebars depends on the testing apparatus; in the present experimental campaign, these were cut with a total length of 1 m and thus their free length varied depending on the anchorage length but more than enough to adequately perform the test. The combination of these variables (two rebars' diameter and three anchorage lengths) with the four NCA by RCCA replacement ratios led to 24 different sets of pull-out specimens. For each of these, three equal specimens were produced, thus leading to a total of 72 specimens (Fig. 1).

The pull-out test consists on applying a tensile force to the steel rebar anchored to the specimen, by means of a hydraulic testing machine equipped with jaws. The movement of the concrete bulk is restrained by means of a fixed steel plate with a hole in the middle, crossed by the steel rebar. The pull out force is applied with displacement control at a constant speed of 0.03 mm/s. Both this parameter and the steel rebar slippage are registered using respectively a load cell and an LVDT, connected to a data logger. The pull-out test set-up is illustrated in Fig. 2. An illustrative curve of the performed pull-out tests is presented in Fig. 3.

4. Results analysis and discussion

4.1. Aggregates tests

Table 2 summarizes the results of all characterization tests of the aggregates used in this experimental program. As expected, RCCA have lower density than NCA, which is justified by the lower density and higher porosity of the cement paste bonded to these, which also justifies their lower apparent bulk density. The obtained values of water absorption and water content are equally

Table 1
Composition of the four concrete mixes.

Type of concrete		RC	RAC20	RAC50	RAC100
	Sieve range (mm)	Mass (kg/m^3)			
NCA	16–22.4	351.1	282.0	175.6	–
	11.2–16	348.5	279.3	72.9	–
	8–11.2	119.7	95.8	61.2	–
	5.6–8	119.7	95.8	58.5	–
	4–5.6	103.7	82.5	53.2	–
RCCA	16–22.4	–	58	165	294.4
	11.2–16	–	57.4	162.5	292.1
	8–11.2	–	20.1	57.5	100.4
	5.6–8	–	20.1	56.25	100.4
	4–5.6	–	17.8	48.75	87.0
NFA	Coarse sand	500.4	500.4	500.4	500.4
	Fine sand	263.9	263.9	263.9	263.9
Cement		350	350	350	350
Effective water		183.6	183.6	183.6	183.6
Compensation water		0	5.5	13.9	27.8

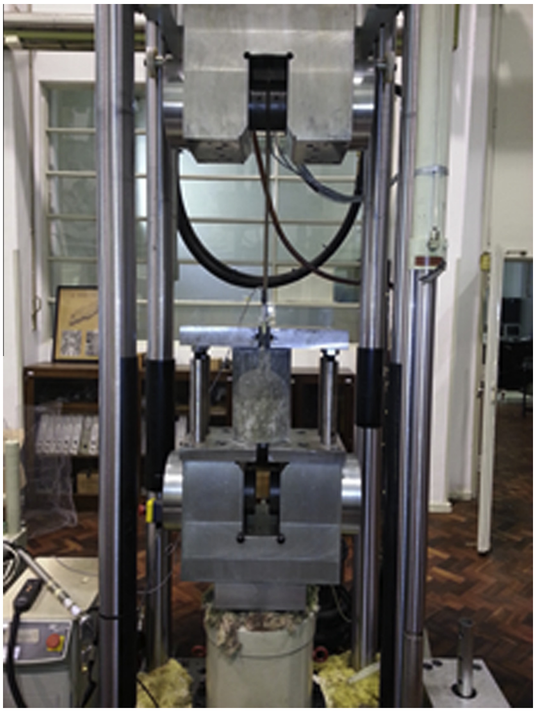

Fig. 2. Pull-out test set-up.

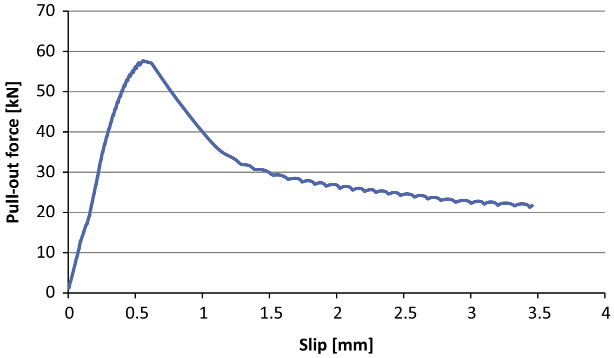

Fig. 3. Representative curves from the pull-out test.

Table 2
Results of the aggregates tests.

Test/aggregate type	NCA	RCCA	Coarse sand	Fine sand
Particles density (kg/m^3)	2685.3	2230.4	2621.1	2627.9
Water absorption at 24 h (%)	0.95	6.57	0.42	0.31
Apparent bulk density (kg/m^3)	1325.3	1233.9	1523.1	1512.6
Water content (%)	1.27	3.42	0.2	0.1
Shape index (%)	13.7	22.1	–	–
Los Angeles wear (%)	24.6	41.1	–	–

coherent with those found in the literature. The higher porosity of the bonded cement paste leads to an increase of the capacity of RCCA to absorb water, originating the substantial differences relatively to the NCA. This cementitious paste bonded to the RCCA also gives rise to more elongated shapes being noticed on the shape index results. In terms of mechanical strength, assessed through the Los Angeles test, the higher brittleness of RCCA, due to the bonded cement paste, leads to a mass loss of these aggregates considerably higher than that of NCA, although below 50% (a value commonly accepted as the limit for application of aggregates in structural concrete [28]).

Table 3
Results of the fresh-state concrete tests.

Test/concrete mix	RC	RAC20	RAC50	RAC100
Slump (mm)	120	120	125	130
Density (kg/m^3)	2370.9	2340.6	2315.2	2244.4

4.2. Fresh-state concrete tests

Table 3 summarizes the results of all tests conducted to characterize the adopted concrete mixes in the fresh state. Concerning workability, the slump value of all mixes fit within the S3 consistency class, as a result of the water compensation to take into account the higher absorption of the RCCA.

The density decrease with the increase of the replacement ratio of NCA by RCCA was expected, given that the density of the aggregates influences the density of the mix.

4.3. Characterization tests of hardened-state concrete

Table 4 presents the results of the characterization tests of the adopted four concrete mixes in the hardened state. For each property the percentile variation relative to the RC is also presented.

It is noticed a slight increase of the compressive strength for the mix corresponding to 20% replacement ratio of RCCA by NCA in relation to the RC. For the mix with 50% replacement ratio of RCCA by NCA, the corresponding loss in strength is not significant, but it becomes noteworthy for a total replacement (100%).

Concerning the splitting tensile strength, a comparable trend is observed, although the 50% and 100% replacement ratios exhibit similar results.

The strength loss registered in both compressive and splitting tests mentioned above can be attributed to the lower mechanical strength of the RCCA (largely referred to in the literature review [3–6,8,9]). Regarding the slight improvement observed for the mix with a 20% NCA by RCCA replacement ratio, this can be related to an increase of the global cement content of the mix, due to the presence of non-hydrated cement particles in the RCCA, as well as to their higher roughness, leading to a better bond of the aggregates to the new cement paste. The first effect was also observed by Fonseca et al. [6] and Evangelista and de Brito [8], and the second one was also detected by Poon et al. [29]. The reason why the strength increase is only registered for low NCA by RCCA replacement ratios (20% in the present study), and not for higher ratios (50% and 100% in the present study), has to do with the fact that the lower mechanical strength of RCCA becomes dominant in the latter situation.

Lastly, a decrease in the Young's modulus was observed with the increase of the NCA by RCCA replacement ratio. This was expected since this parameter is directly influenced by the aggregates' stiffness [7], and RCCA are less stiff than NCA.

4.4. Pull-out tests

The results of the pull-out tests performed with 12 mm diameter ribbed steel rebars at 70 days of age are presented in Table 4, and the corresponding values obtained with 16 mm diameter ribbed steel rebars are presented in Table 5.

It must be stressed that all specimens exhibited a splitting failure mode (Figs. 4 and 5), as planned since the anchorage lengths were chosen to prevent yielding of the steel rebars. Concrete failure was also avoided by considering a low diameter hole in the mentioned steel plate used to restrain the vertical displacement of the concrete bulk of the pull-out specimen. This way, failure was enforced at the rebar-to-concrete interface, leading first to bond failure and then to splitting failure due to the rebar ribs (combined with lack of confinement).

Table 4
Results of the hardened-state concrete tests.

Property/concrete mix	RC	RAC20	$\Delta_{RAC20-RC}$ (%)	RAC50	$\Delta_{RAC50-RC}$ (%)	C100	$\Delta_{RAC100-RC}$ (%)
Compressive strength at 7 days (MPa)	34.7	37.2	+7.2	36.3	+4.6	30.4	−12.4
Compressive strength at 28 days (MPa)	48.5	49.3	+1.6	47.9	−1.2	43.4	−10.5
Compressive strength at 56 days (MPa)	52.7	52.8	+0.2	49.1	−6.8	45.7	−13.3
Splitting tensile strength at 28 days (MPa)	3.95	3.96	+0.3	3.61	−8.6	3.63	−8.1
Modulus of elasticity at 28 days (GPa)	37.6	37.2	−1.1	34.5	−8.2	33.0	−12.2
Abrasion resistance at 91 days (mm)	3.52	3.52	−0.1	2.96	+15.93	3.67	−4.22

4.4.1. Analysis of the influence of RCCA incorporation

Fig. 6 illustrates the evolution of the pull-out forces with the NCA by RCCA replacement ratio. Linear regression trend-lines were considered which show that the pull-out force decreases with the increase of the replacement ratio of NCA by RCCA. Regarding both the compressive strength and the splitting tensile strength, an increase of the pull-out force is observed for 20% NCA by RCCA replacement ratio, suggesting that the increase in the cement content that resulted from the RCCA incorporation (as explained before) can be also responsible by an enhancement of the bond between steel rebars and RCCAC, for low replacement ratios. For 50% NCA by RCCA replacement ratio, there is a slight decrease in comparison to the strength obtained with the RC. Finally, for 100% NCA by RCCA replacement ration, a significant decrease in the anchorage strength was registered, suggesting as before for the RAC mechanical properties, that for NCA by RCCA replacement ratios higher than 50%, the brittleness of RCCA becomes predominant over the influence of the increase in the cement content.

In summary, the decrease of the pull-out force registered in the RAC20, RAC50 and RAC100 mixes, compared to the one obtained in the RC, was respectively: +7.07%, −5.67% and −12.25%. Based on this result, and in what concerns ribbed steel rebar-to-concrete bond, it can be stated that RCCA can be used in structural concrete for NCA by RCCA replacement ratios up to 50%, since this does not cause significant anchorage force losses.

Fig. 4. Cracking at the upper surface of the specimen.

Fig. 5. Vertical cracking plan of the specimen.

4.4.2. Analysis of the influence of anchorage length

To analyse the influence of the anchorage length on the anchorage strength of steel rebars to RCCAC, first the steel rebars used in this experimental campaign (three specimens of each type) were tested, being the results presented in Table 7. Then, knowing the tensile strength of the steel rebars, the upper limit of the anchorage length was settled, i.e. the maximum force corresponding to steel rebar failure in tension, instead of anchorage failure.

The study of this parameter included the analytical estimation of the anchorage strength according to the design procedure proposed by Model Code 2010 [30]. This document specifies different approaches to be used according to the adopted test and expected

Table 5
Results of the pull-out tests for 12 mm diameter steel rebars.

Concrete mix	Anchorage length	Pull-out force (kN)	Δ_{RC} (%)	Standard deviation (kN)
RC	5ϕ	34.25	–	2.65
	10ϕ	45.75	–	2.97
	15ϕ	54.53	–	4.33
RAC20	5ϕ	34.67	+1.21	3.13
	10ϕ	54.21	+18.51	4.64
	15ϕ	58.18	+6.69	1.10
RAC50	5ϕ	31.95	−6.73	2.76
	10ϕ	47.73	+4.34	2.45
	15ϕ	53.13	−2.57	3.49
RAC100	5ϕ	27.07	−20.98	1.56
	10ϕ	43.20	−5.57	0.56
	15ϕ	48.51	−9.22	2.50

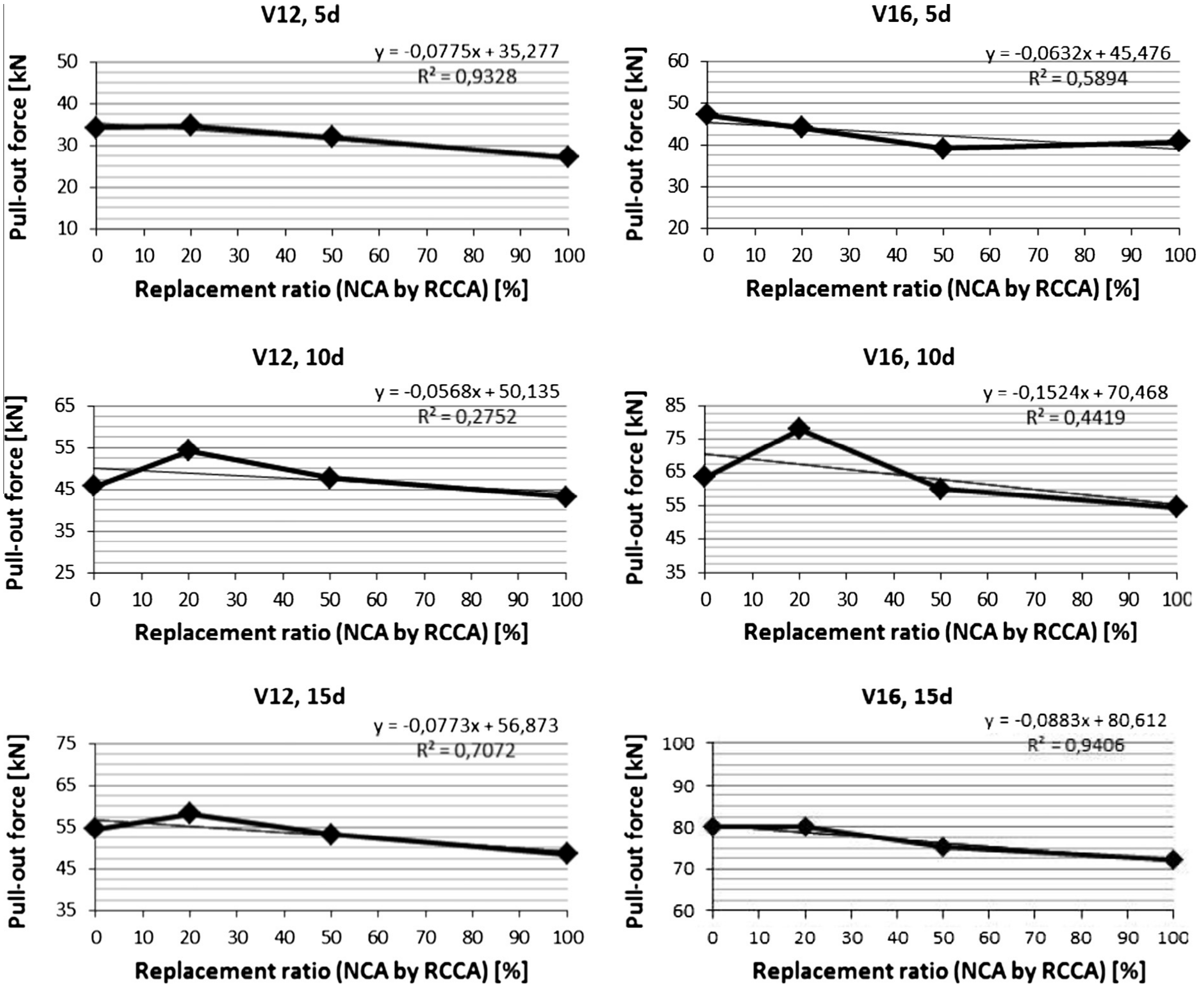

Fig. 6. Pull-out force versus RCCA by NCA replacement ratio.

failure modes. In this campaign the latter was always splitting by radial cracking (around the steel rebar). For this situation, Model Code 2010 proposes the following equation for the maximum bond stress ($\tau_{\max}$):

$$\tau_{\max} = 7 \times \left(\frac{f_{ck}}{20}\right)^{0.25} \qquad (1)$$

Since not enough tests were performed in our campaign to determine characteristic values of the concrete's compressive strength, the option was to use the average value f_{cm} instead of the characteristic value f_{ck} proposed by the equation.

After collecting all the data, anchorage strength versus anchorage length curves were drawn (Fig. 7), including both the experimental results and the theoretical values given by Eq. (1), as well as critical values corresponding to both yielding and failure of the steel rebars. Fig. 7 an illustrative example of this analysis is presented, corresponding to the RAC100 specimens with 12 mm diameter rebars.

An almost linear correlation (R^2 = 0.94) between the anchorage strength and the anchorage length is found for all anchorage lengths considered. This was expected since there is an increase of the contact area between the steel rebars and concrete with the increase of the anchorage length.

Table 6
Results of the pull-out tests for 16 mm diameter steel rebars.

Concrete mix	Anchorage length	Pull-out force (kN)	Δ_{RC} (%)	Standard deviation (kN)
RC	5ϕ	47.13	–	1.20
	10ϕ	63.52	–	10.58
	15ϕ	80.24	–	5.08
RAC20	5ϕ	44.16	−6.31	1.54
	10ϕ	77.89	+22.63	6.71
	15ϕ	80.00	−0.3	5.89
RAC50	5ϕ	39.09	−17.06	3.32
	10ϕ	59.99	−5.56	4.74
	15ϕ	75.09	−6.41	2.47
RAC100	5ϕ	40.78	−13.48	3.14
	10ϕ	54.56	−14.11	3.85
	15ϕ	72.10	−10.14	3.03

Table 7
Pull-out strength of the steel rebars.

Steel rebar	Diameter (mm)	F_y (kN)	F_u (kN)	$F_{y,m}$ (kN)	$f_{y,m}$ (MPa)	$F_{u,m}$ (kN)	$F_{u,m}$ (MPa)
V12_1	12	61.76	72.67	62.3	550.85	73.09	646.26
V12_2	12	61.93	72.85				
V12_3	12	63.91	73.84				
V16_1	16	105.75	122.8	106.96	531.98	124.08	617.12
V16_2	16	107.03	124.04				
V16_3	16	108.09	125.41				

Concerning the experimental versus the analytical values, there is a slight difference of slope between the corresponding curves, nevertheless generally providing a satisfactory prediction of the anchorage strength, and most probably within the confidence interval of the experimental results. In addition, for an anchorage length of 15ϕ, the theoretical value is very close to the yielding force of the steel rebar. Therefore, a mixed failure mode, combining yielding initiation of the steel rebar with steel rebar-to-concrete bond failure, can also lead to an anchorage strength lower than predicted.

In the experimental tests slight differences were observed in the failure mode of specimens as a function of the anchorage length. For specimens with higher anchorage lengths (10ϕ and 15ϕ), the propagation of radial cracking around the steel rebar was also more significant (Fig. 4). Moreover, for these specimens, cracks occurred throughout the specimen's height thus causing split of the specimen. In Fig. 5 the cracking plan is shown for one of these cases.

4.4.3. Analysis of the influence of steel rebar diameter

As expected, the increase of the steel rebar diameter led to an increase of the anchorage strength, since the contact area between the steel rebar and concrete also increased (for the same anchorage length).

However, some differences in the failure mode of specimens with 12 mm and 16 mm ribbed steel rebars were observed. The former exhibited more radial cracks around the steel rebar and thus lower crack widths, whereas the latter showed less and thus wider radial cracks, as illustrated in Fig. 12.

5. Numerical modelling

To analyse the stress distribution within the pull-out specimens, numerical models were developed for each of the 24 different specimens types, using the commercial finite element code Abaqus CAE [31]. The main goal of this numerical approach was to better understand the influence of each considered parameter on both the anchorage strength and the failure mode of ribbed steel rebars to RAC.

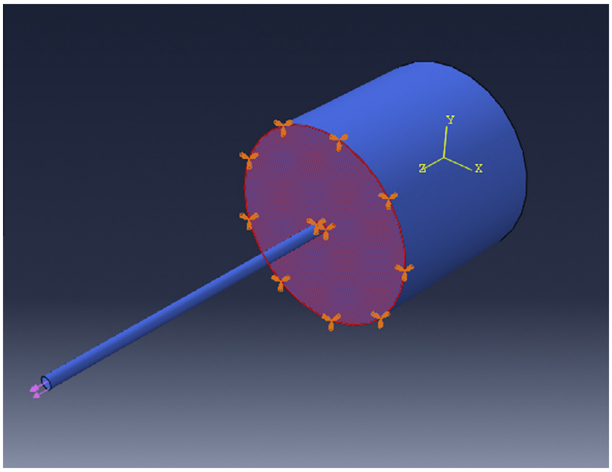

Fig. 8. Boundary conditions and loading of the numerical model.

5.1. Adopted models

The numerical models were built to take into account the different geometry of steel rebars the different material properties of the concrete bulk. The boundary conditions and loading of pull-out specimens were also adequately simulated.

First, the definition of the finite element mesh was object of various trials. A mesh with 5 cm elements was adopted for having enough precision. The adopted material properties of concrete, namely the Young's modulus, and the bond strength between steel rebars and concrete were based on the experimental results (Tables 4–6). It should be highlighted that only a linear elastic analysis was conducted and thus only the stress distribution at the beginning of the pull-out test can be analysed, since afterwards slip between the steel rebar and concrete occurs. In the models, no relative slip was considered in the interface between the two materials. The boundary conditions of the pull-out specimen, materialized by a steel plate in the experimental tests, were modelled by restraining both displacements and rotations of the corresponding points. Finally, loading was applied in the free end of the rebar, as in the experimental test. The anchorage forces obtained in

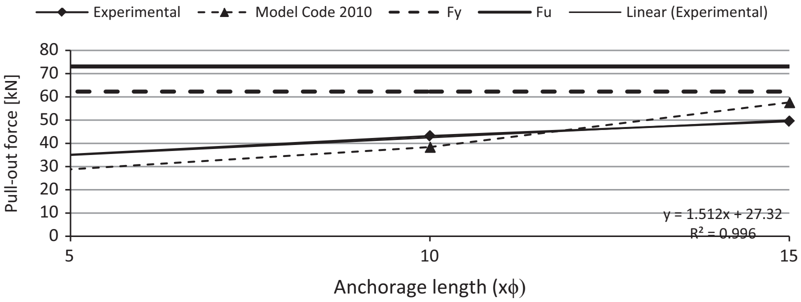

Fig. 7. Pull/out force vs. anchorage length (experimental and MC 2010 values).

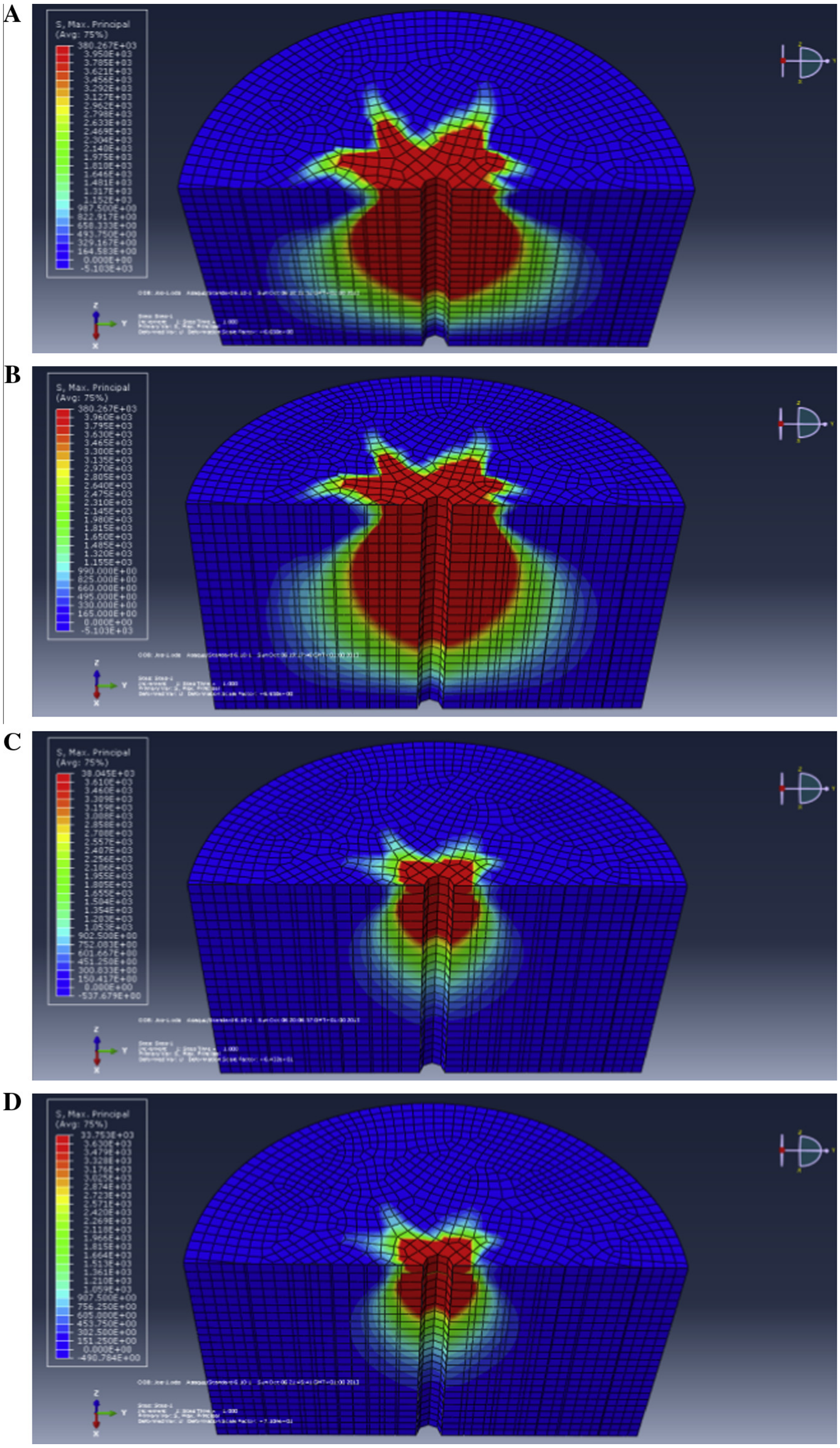

Fig. 9. Stress distribution vs. concrete type.

the experimental tests were applied as loading of the numerical models. Both boundary conditions and loading of the numerical model are represented in Fig. 8.

5.2. Presentation and discussion of the results

The results are presented graphically, allowing visualizing the model's stress distribution, both in the interception surface of the rebar and within. The elements with stresses higher than the experimental splitting tensile strength of the corresponding concrete mix (as shown in Table 4) are represented in red. Blue represents stress values equal to or below zero, i.e. subjected to compression. The stresses presented in the models correspond to maximum values in the principal directions of the element.

5.2.1. Analysis of the influence of the NCA by RCCA replacement ratio on stress distribution

The influence of the NCA by RCCA replacement ratio on the stress distribution is mainly related with the elastic properties and the failure mode (splitting). This means that the expected

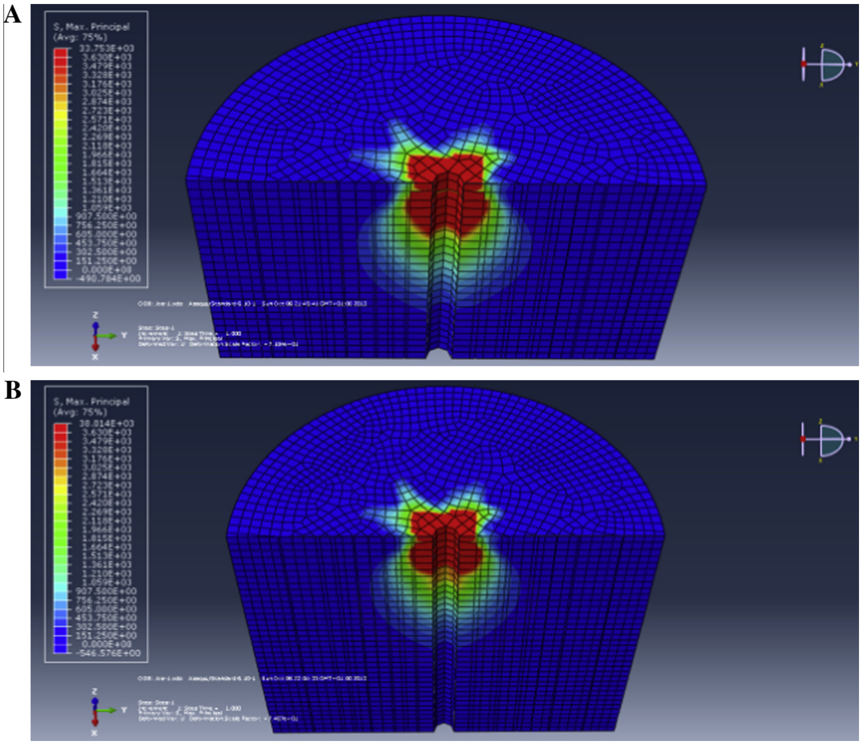

Fig. 10. Stress distribution vs. anchorage length.

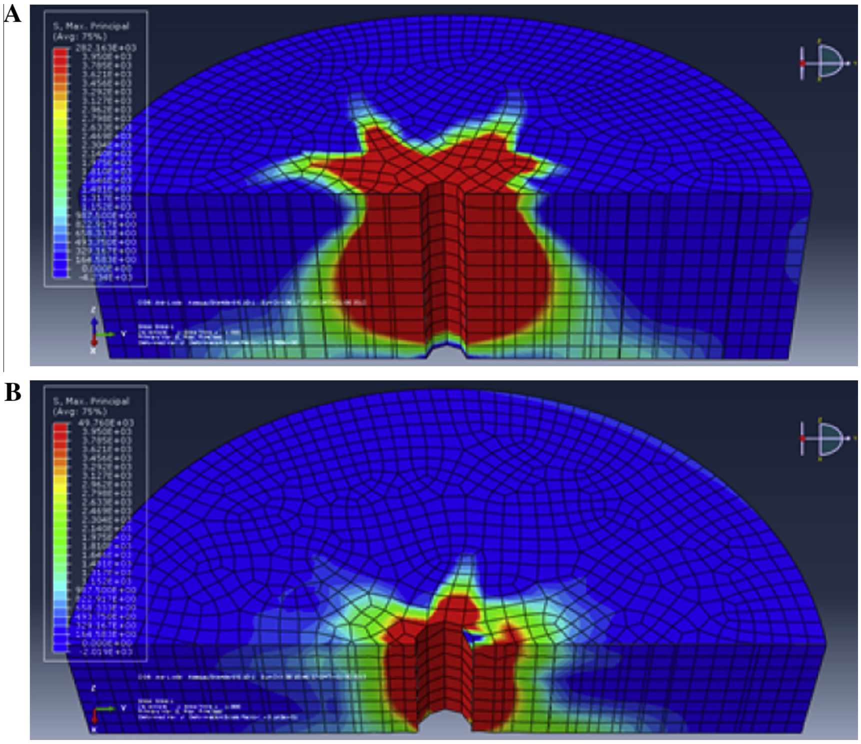

Fig. 11. Stress distribution vs. steel rebar diameter.

trends are similar to those of concrete's splitting tensile strength. In fact, failure occurred for lower stresses for specimens made with concrete mixes with higher NCA by RCCA replacement ratios (RAC50 and RAC100). In Fig. 9, the stress distributions of four specimens with the same geometry (12 mm diameter steel rebar and 10ϕ anchorage length) but different concrete types – RC (A), RAC20 (B), RAC50 (C) and RAC100 (D), are presented.

5.2.2. Analysis of the influence of anchorage length on stress distribution

The anchorage length does not seem to have any influence on the stress distribution shape. In fact, the increase of the steel rebar anchorage length only stretches the stress field in height. However, for lower anchorage lengths, it is observed that the tensioned zone has higher relative importance. This is illustrated in Fig. 10, where

Fig. 12. Failure modes vs. steel rebar diameter.

two RAC100 specimens with a 12 mm rebar and anchorage lengths of 10ϕ (A) and 15ϕ (B) are presented.

5.2.3. Analysis of the influence of steel rebar diameter on stress distribution

Changing the steel rebar diameter led to significant changes in terms of stress distribution, both on the upper surface of the specimen and along the anchorage length of the steel rebar.

When 12 mm diameter steel rebars are used, independently of other variables, the distribution of stresses exhibits more branches (representing potential cracks) than in the case where 16 mm diameter rebars are adopted. In the former case, eight or more branches between 30 and 50 mm long appear and, in the latter situation, less than six branches between 18 and 36 mm appear. In Fig. 11, the stress distribution obtained for RC specimens with 12 mm (A) and 16 mm (B) rebars, both with 5ϕ anchorage length, is presented. These numerical results are in agreement with the experimental results, where specimens with 12 mm steel rebars exhibited larger number of longer radial cracks than the specimens with 16 mm steel rebars, which often split by one plane only. In Fig. 12, failure mode of RAC20 specimens with 12 mm (A) and 16 mm (B) diameter steel rebars and 10ϕ of anchorage length are shown.

6. Conclusions

The following conclusions are drawn concerning the anchorage force of steel rebars to RCCAC and the variables under analysis:

- There is a general trend of anchorage force loss as the replacement of NCA by RCCA increases, especially for total substitution (on average −12.25%); at 50% replacement average losses of anchorage force are not significant (−5.66%) while at 20% slight improvements (on average +7.07%) were registered.
- These trends follow closely those found concerning the influence of the replacement of NCA by RCCA on concrete's splitting tensile strength; this is because the failure mode of the specimens was consistently by splitting, and therefore conditioned by concrete's tensile strength.
- The steel rebar's anchorage length has no influence on the stress distribution in the interface steel–concrete, independently of the replacement ratio of NCA by RCCA; the relative importance of the tensioned concrete area only increases for low anchorage lengths.
- The steel rebar diameter is preponderant on the stress distribution in the interface steel–concrete; for 12 mm rebars there is a greater propagation of radial tensile stresses, which branched on the surface and varied along the rebar's length; on the other hand, for 16 mm rebars the stress distribution is less branched and widespread and more uniform along the rebar's length; these trends are coherent with the failure modes observed in the experimental tests.
- Based on these study's results, it is expected that the incorporation of RCCA in structural concrete up to 50% will not lead to significant losses of anchorage force of steel rebars to concrete.

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References

[1] European Commission. Promoting sustainable development in the non-energy extractive industry. Brussels: Communication from the Commission; 2000.
[2] European Commission. Service contract on management of construction and demolition waste – SR1. Final report; 2011.
[3] Matias D, de Brito J, Rosa A, Pedro D. Mechanical properties of concrete produced with recycled coarse aggregates – influence of the use of superplasticizers. Constr Build Mater 2013;44:101–9.
[4] Gonçalves A, Neves R. Recycled aggregates (in Portuguese). Seminar in aggregates. Personal communication. Lisbon (Portugal): LNEC; 2003.
[5] Kou S, Poon C. Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. Cement Concr Compos 2013;37:12–9.
[6] Fonseca N, de Brito J, Evangelista L. The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. Cement Concr Compos 2011;33:637–43.
[7] Coutinho A, Gonçalves A. Production and properties of concrete, vol. I, II and III. LNEC; 1997 (in Portuguese).
[8] Evangelista L, de Brito J. Mechanical behavior of concrete made with fine recycled concrete aggregates. Cement Concr Compos 2007;29:397–401.
[9] Gomes M, de Brito J. Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance. Mater Struct 2009;42(5):663–75.
[10] Xiao J, Falkner H. Bond behavior between recycled aggregate concrete and steel rebars. Constr Build Mater 2007;21:395–401.
[11] Kim S, Yun H. Influence of recycled coarse aggregates on the bond behavior of deformed rebars in concrete. Eng Struct 2012;48:133–43.
[12] Butler L, West J, Tighe S. The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement. Cem Concr Res 2011;41:1037–49.
[13] Gonçalves P, de Brito J. Recycled aggregate concrete (RAC) – comparative analysis of existing specifications. Mag Concr Res 2010;42(5):339–46.
[14] EN 933-1. Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution. Sieving Method 2000.
[15] EN 1097-6. Tests for mechanical and physical properties of aggregates. Part 6: Determination of density and water absorption 2003.
[16] EN 1097-3. Tests for mechanical and physical properties of aggregates. Part 3: Determination of loose bulk density and voids 2003.
[17] EN 1097-5. Tests for mechanical and physical properties of aggregates. Part 5: Determination of water content 2011.
[18] LNEC E-237. Wear test using the Los Angeles machine (in Portuguese) 1970.
[19] EN 933-4. Tests for geometrical properties of aggregates. Part 4: Determination of particle shape. Shape index 2002.
[20] Ferreira L, de Brito J, Barra M. Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. Mag Concr Res 2011;63(8):617–27.
[21] EN 12350-2. Testing of fresh concrete. Part 2: Slump test 2002.
[22] EN 12350-6. Testing of fresh concrete. Part 6: Density 2002.
[23] EN 12390-3. Testing of hardened concrete. Part 3: Compressive strength of test specimens 2003.

[24] EN 12390-6. Testing of hardened concrete. Part 6: Tensile splitting strength of test specimens 2004.
[25] LNEC E 397. Concrete: Determination of elasticity modulus in compression (in Portuguese). LNEC; 1993.
[26] Jorge S, Dias-da-Costa D, Júlio E. Influence of anti-corrosive coatings on the bond of steel rebars to repair mortars. Eng Struct 2012;36:372–8.
[27] RILEM/CEB/FIP. Recommendations on reinforcement steel for reinforced concrete. Revised edition of RC6 of bond test for reinforcement steel: (2) Pull-out test, revised edition; 1983.
[28] Alexander M, Mindess S. Aggregates in concrete. Mod. Concr. Technol. 2005;13:448–9.
[29] Poon C, Shui Z, Lam L, Fok H, Kou S. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. Cem Concr Res 2004;34:31–6.
[30] fib Model Code for concrete structures; 2010.
[31] Abaqus/CAE software. Dessault Systémes Simulia Corp.