Cement & Concrete Composites 34 (2012) 1044–1052

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates

P. Pereira [a], L. Evangelista [b], J. de Brito [a,*]

[a] Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[b] Instituto Superior de Engenharia de Lisboa, R. Conselheiro Emídio Navarro, 1, 1959-001 Lisbon, Portugal

ARTICLE INFO

Article history:
Received 28 May 2012
Received in revised form 14 June 2012
Accepted 16 June 2012
Available online 26 June 2012

Keywords:
Fine recycled aggregate
Superplasticizers
Concrete
Tensile strength
Modulus of elasticity
Abrasion

ABSTRACT

It is considered that using crushed recycled concrete as aggregate for concrete production is a viable alternative to dumping and would help to conserve abiotic resources. This use has fundamentally been based on the coarse fraction because the fine fraction is likely to degrade the performance of the resulting concrete. This paper presents results from a research work undertaken at Instituto Superior Técnico (IST), Lisbon, Portugal, in which the effects of incorporating two types of superplasticizer on the mechanical performance of concrete containing fine recycled aggregate were evaluated. The purpose was to see if the addition of superplasticizer would offset the detrimental effects associated with the use of fine recycled concrete aggregate.

The experimental programme is described and the results of tests for splitting tensile strength, modulus of elasticity and abrasion resistance are presented. The relative performance of concrete made with recycled aggregate was found to decrease. However, the same concrete with admixtures in general exhibited a better mechanical performance than the reference mixes without admixtures or with a less active superplasticizer. Therefore, it is argued that the mechanical performance of concrete made with fine recycled concrete aggregates can be as good as that of conventional concrete, if superplasticizers are used to reduce the water–cement ratio of the former concrete.

1. Introduction

1.1. Preliminary remarks

The continuous exploitation of raw materials, especially non-renewable resources, for construction and the problems arising from treating millions of tonnes of construction and demolition waste (CDW) every year are present-day challenges that the construction industry must address. Within this context the use of recycled aggregate (RA) may prove to be a viable alternative that can tackle both challenges in a sustainable way.

The initial reviews on the use of RA, in particular by Nixon [1] and Hansen [2], focused on their increased worth and reported the first results on the mechanical performance and durability of the concrete. There was common ground in that the use of coarse recycled aggregate (CRA) is viable, notwithstanding a decrease in performance, which can also be mitigated through different approaches [3,4], and the results for concrete containing fine recycled aggregate (FRA) were consistently negative, leading to a recommendation to not incorporate them. More recent reviews reveal that the incorporation of RA, particularly fine and coarse concrete aggregate, has good potential because of their hydraulic properties [5]. Recent works have established knowledge bases that allow the unrestricted use of concrete CRA in new concrete. Results for mechanical performance [6–8], the effects of curing conditions [9,10], the use of self-compacting concrete [11,12] and high-performance concrete [13] show that in terms of their specific characteristics CRAs can be considered to be the same as natural aggregate. In terms of durability it is agreed that concrete made with RCA performs worse [14,15], and therefore should not be exposed to aggressive environments.

Even though the incorporation of FRA in concrete is generally associated with adverse effects on its compressive strength [12,16,17], the results reported by Evangelista and de Brito [18] show that it is feasible to produce fine recycled aggregate concrete (FRAC) for structural purposes. Leite [19] also notes that the use of FRA in structural concrete may have a positive impact due to non-hydrated cement from the source concrete and an improved mortar/recycled aggregate interface thanks to the larger specific surface of the RA. The durability of FRAC is lower than that of conventional concrete [20] and that of concrete made with CRA.

* Corresponding author.
E-mail address: jb@civil.ist.utl.pt (J. de Brito).

0958-9465/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cemconcomp.2012.06.009

1.2. Splitting tensile strength

Even though it is considered by some as a property of lesser importance in concrete, tensile strength has a major role in reinforced concrete design, either directly or indirectly, as some of its key calculations depend on it [21]. Initial works indicate that the trends found in compressive strength of FRAC, in particular those concerning the w/c ratio, will be the same for tensile strength, even if less marked [22]. Therefore if the tensile strength of a FRAC is found to be lower than that of the corresponding reference mix without RA (RC), this is probably because of an increase in the w/c ratio to compensate for the additional water absorption of the FRA and the loss of workability due to its incorporation. More recent research [18] has contested this trend by showing significant decreases in the tensile strength even though the compressive strength remains approximately constant. This seems to contradict general knowledge [23] that tensile strength has a direct relationship with compressive strength. Leite [19] showed that for higher w/c ratios the incorporation of FRA is beneficial to the splitting tensile strength whilst for smaller ratios it is detrimental. Solyman [24] found splitting tensile strength reductions of up to 18.8% in FRAC with 70% FRA incorporation compared with the RC. Evangelista and de Brito [18] concluded that tensile strength is affected by FRA incorporation, i.e. there is a reduction up to 23% by comparison with the RC.

1.3. Modulus of elasticity

The modulus of elasticity is a prime property of concrete, as it defines the deformability of structures and the interaction between reinforcement and concrete. The modulus of elasticity of FRACs is lower than the corresponding control mixes, which is commonly attributed to the mortar adhered to the original aggregates, a characteristic of recycled concrete [2]. Khatib [16] compared the modulus of elasticity of FRAC with that of the corresponding RC and found reductions of up to 32% for 100% FRA incorporation. He also found that the impact of FRA is less for incorporation ratios between 25% and 75% and that it increases with curing time. Solyman [24] concluded that even though replacing fine natural aggregates (FNA) with FRA leads to lower concrete moduli of elasticity, this effect is attenuated if the size distribution of the RA is adjusted. He also found that the quality of the FRA has a great influence on lowering the modulus of elasticity; he noted that FRAs with greater porosity and water absorption potential performed worst, a phenomenon also reported by Corinaldesi and Moriconi [25]. For Evangelista and de Brito [18] FRA incorporation led to the concrete's modulus of elasticity falling by up to 18.5% compared with that of the RC.

1.4. Abrasion resistance

The abrasion of concrete structures is a phenomenon mostly associated with hydraulic structures, where there is permanent contact with moving fluids, most of the times transporting waterborne gravel and debris [26] and with industrial concrete floors [27]. Wear resistance is improved by such aspects as a reduction of the w/c ratio, an increase in cement content, and avoiding premature loss of water from the cement paste or excessive water dilution in the concrete surface [28]. The following factors have the most influence on the abrasion resistance of FRAC: effective w/c ratio, porosity/irregularity of the aggregates surface, binder content [29]. Evangelista and de Brito [18] observed an abrasion resistance around 20% higher in FRAC with 100% FRA than in the respective RC. The authors suggest that this is caused by a better bond between the cement paste and the FRA, because of its porosity.

2. Scope and method

The characteristics of the RA, the concrete composition and the type of superplasticizer all markedly influence the mechanical performance of RAC. Even though there is considerable knowledge about the two first factors, little work has been published on the effects of superplasticizers on FRAC. Although it seems obvious that the inclusion of superplasticizers will improve mechanical performance, it is still to be determined if its effect will offset the presence of lower-grade aggregates and if the performance of FRAC differs as a function of the superplasticizers' water-reducing capacity. Therefore this paper intends to analyse the influence of FRA on the mechanical performance of concrete and simultaneously consider the effect of adding superplasticizers on FRAC and RC. Superplasticizers are powerful water reducers that enable an increase in the ultimate stress of concrete by decreasing the w/c ratio, a decrease in the cement content while maintaining the same range of strength or workability, an increase in concrete compacity, and other effects [30]. In this context the deflocculation mechanism of polycarboxylic-based superplasticizers is more efficient since it leads to two repulsive forces between the cement particles: electrostatic repulsion due to a negative charge caused by the carboxylic group and steric repulsion from the presence of long polymeric chains on the aggregate's surface. The combination of these effects could enable water reductions of up to 40% [31].

The FRAs used throughout the experimental programme were obtained from a source concrete (SC) produced by a ready-mixed concrete plant and moulded in the laboratory. This procedure meant that the component materials were known, the concrete production was controlled and its main characteristics were understood. The crushed material was separated first into two fractions, above and below 4 mm, and afterwards according to the EN 933-1 standard [32] sieve sizes, allowing the size distribution of the FNA to be replicated exactly. Concrete mixes without admixtures (WS), with current superplasticizer (SP 1) and with high-performance superplasticizer (SP 2) were produced. Five mixes were prepared for each admixture, with different incorporation ratios of FRA. In order to have a comparative basis to work on it was established that all mixes would have a slump (Abrams cone) of 120 ± 10 mm. The influence of the superplasticizers on the compressive strength and the w/c ratio needed to keep the slump constant has been discussed in detail in another paper [33].

This paper focuses on the influence of superplasticizers on the splitting tensile strength, modulus of elasticity and abrasion resistance of concrete made with recycled concrete aggregate.

3. Experimental programme

3.1. Source concrete (SC)

The SC was provided by a ready-mixed concrete plant, moulded in the laboratory and subjected to current curing conditions. It was designed to be a C30/37.X0(P).S3.Cl0.40.D_{max}25 concrete, according to NP EN 206-1 [34]. The slump (Abrams cone) was 120 mm and 28 day compressive strength (in 150 mm cubes) was 37.3 MPa. Table 1 details the composition of the SC.

3.2. Characterisation of the aggregates

After 28 days of curing the blocks of SC were crushed using a jaw crusher and a setting that maximised the amount of fines produced. FRA were stored in the lab, inside plastic containers that kept moisture and temperature constant. All test specimens were cast within a period of 3 months after crushing.

Table 1
Source concrete (SC) composition.

	Content (kg/m^3)
Cement II/A-L 42.5R	224
Fly ash	121
Water	165
Fine natural sand	216
Coarse natural sand	437
Fine natural limestone gravel	215
Medium natural limestone gravel	326
Coarse natural limestone gravel	633
Plasticizer	3.45

These experiments used two types of siliceous sands and two limestone coarse aggregates, as well as FRAs. All aggregates were characterised in terms of size grading [32] particle density and water absorption [35] and loose bulk density [36]. The shape index [37] and Los Angeles wear [38] were determined for the coarse natural aggregates (CNA). The analysis is presented in Table 2. The size distribution of the FRA is the same as that used in the mixes design (Fig. 1) and exactly replicated the FNA distribution.

Table 2 shows that the natural aggregates (NA) have similar characteristics within each size fraction. The FRAs have lower particle densities and loose bulk densities than the FNAs. This is due to the adhered mortar that increases the FRAs' porosity. The FRA water absorption, 10.9%, is clearly higher than that of the FNA.

3.3. Superplasticizers used

Two types of superplasticizer were used: a current one henceforth called SP 1, whose chemical basis is lignosulfonate, with additions; a high-performance superplasticizer, henceforth called SP 2, whose chemical basis is a combination of modified polycarboxylates in an aqueous solution. Two reference concrete mixes with superplasticizer (RC1 and RC2) were prepared in addition to the reference concrete without admixtures (RC0), all without RA. When used, the superplasticizer content was kept constant at 1% of the cement mass. To keep the mixes' workability constant, with slump within the range 120 ± 10 mm, the w/c ratio was reduced in the mixes with superplasticizers to offset the latter's water reduction effect.

3.4. Concrete mixes' composition

Based on Faury's method [39] five mixes were produced for each superplasticizer (and also without admixtures): a reference concrete (RC) and four FRACs with replacement ratios of FNA by FRA of 10%, 30%, 50% and 100%. Faury's method is based on an empirical reference grading curve that optimizes compacity for a given mix, whose main design characteristics are known. All mixes in this experiment have the same de facto aggregate size distribution and cement content. Water reductions that resulted from the use of superplasticizers were offset by an increase in the volume of aggregate. Table 3 presents a summary of the mixes' compositions,

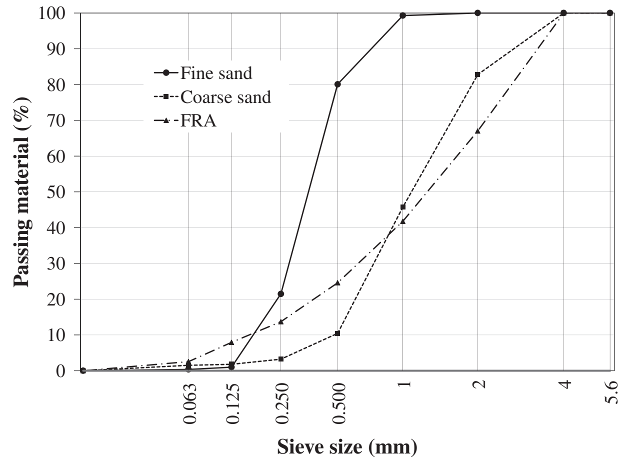

Fig. 1. Grading curves of the FRA and FNA (fine and coarse sand).

where the mixes without RA are CR0 if they have no admixtures, CR1 if they have SP 1 and CR2 if they have SP 2. In each of these families the other mixes are C0, C1 and C2, followed by the percentage replacement ratio of FNA by FRA. Table 3 gives two w/c ratio values per composition: apparent w/c ratio – $(w/c)_{ap}$ – the ratio between the total water in the mix and the cement content; effective w/c ratio – $(a/c)_{ef}$ – the ratio between the water effectively available to lubricate the mix and hydrate the cement, discounting the water that is absorbed during mixing by the FRA, and the cement content.

3.5. FRAC mixes

FRAs have a much higher water absorption potential that cannot be ignored during casting. Just simply replacing NA by the same volume of RA would affect the workability and performance of the concrete. It was thus necessary to understand the evolution of the FRA's water absorption because mixing time was limited (10 min) and absorption takes much longer. By adopting a process suggested by Leite [19] (leading to Fig. 2), it was found that around 50% of the water absorption potential would be reached at the end of the mixing procedures. Therefore, extra water was added to the FRAC mixes. The extra amount was equal to the difference between the amount expected to be absorbed by the FRAs during mixing and the amount within them before they were used (since they were not oven-dried). Further slight corrections of the w/c ratio were needed to keep the slump constant, given the greater friction between the FRA particles and the other concrete components. Final compositions are presented in Table 3.

3.6. Tests on concrete mixes

Every specimen was subjected to curing in a wet chamber as specified in NP EN 12390-2 [40].

Table 2
Natural and recycled aggregates' properties.

	FRA	FNA1	FNA2	CNA1	CNA2
Saturated surface-dry particle density (g/cm^3)	2.23	2.60	2.62	2.64	2.70
Oven-dry density (g/cm^3)	2.01	2.59	2.61	2.62	2.68
Apparent particle density (g/cm^3)	2.57	2.60	2.62	2.67	2.72
Water absorption at 24 h (%)	10.9	0.11	0.19	0.63	0.58
Loose bulk density (g/cm^3)	1.28	1.51	1.55	1.44	1.41
Los angeles abrasion loss (%)	–	–	–	30.8	31.9
Shape index (%)	–	–	–	17.0	10.9
Fineness modulus	3.13	1.98	3.56	6.4	7.57

Table 3
Concrete mixes' composition (1 m^3).

	RC0	C0,10	C0,30	C0,50	C0,100	RC1	C1,10	C1,30	C1,50	C1,100	RC2	C2,10	C2,30	C2,50	C2,100
Replacement ratio (%)	0	10	30	50	100	0	10	30	50	100	0	10	30	50	100
Cement (kg)	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350
Water (l)	193	193	194	196	199	158	158	163	168	178	133	137	139	143	150
w/c Ratio	0.55	0.55	0.56	0.56	0.57	0.45	0.45	0.47	0.48	0.51	0.38	0.39	0.40	0.41	0.43
$(w/c)_{ef}$ ratio	0.55	0.55	0.55	0.55	0.55	0.45	0.45	0.46	0.47	0.49	0.38	0.39	0.39	0.40	0.41
FRA (kg)	0	57	170	283	566	0	59	177	294	582	0	61	183	304	605
FNA1 (kg)	199	179	140	100	0	209	188	145	103	0	216	193	150	107	0
FNA2 (kg)	536	482	375	268	0	561	505	391	278	0	580	520	405	288	0
CNA1 (kg)	275	275	275	275	275	288	288	286	285	282	298	296	296	295	293
CNA2 (kg)	786	786	786	786	786	823	823	819	815	807	851	847	847	843	839
Superplasticizer (kg)	0	0	0	0	0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Slump (mm)	123	123	119	123	112	125	128	129	130	125	130	122	128	121	120

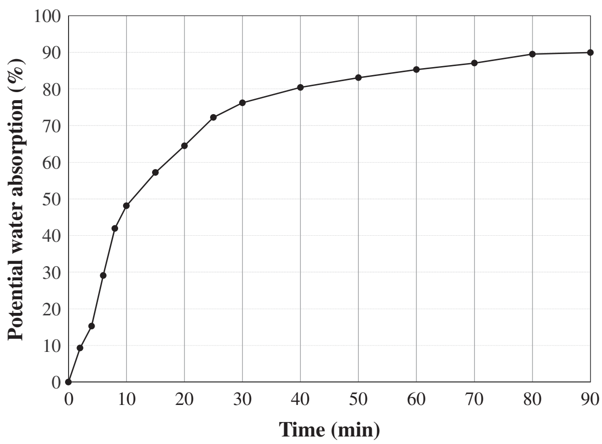

Fig. 2. FRA's water absorption over time.

The test method specified in NP EN 12390-6 [41] was used to determine the splitting tensile strength. Tests were performed on three cylinders 300 mm high and a diameter of 150 mm, per concrete mix analysed. The reliability of this test is well known and has been discussed in various publications [42–44].

The method described by Portuguese specification LNEC E-397 [45] was used to measure the concrete modulus of elasticity, using two cylinders 300 mm high and a diameter of 150 mm, per mix. The standard determines the static secant modulus between stress levels of 1 MPa and around one third of the concrete's ultimate compressive strength.

The determination of the wear resistance by abrasion followed the test method specified in German standard DIN 52108 [46]. Two $71 \times 71 \times 50\ mm^3$ specimens were tested per concrete mix, with nine readings per specimen.

4. Results and discussion

4.1. Splitting tensile strength

The splitting tensile strength results are presented in Table 4 and Fig. 3 as a function of the aggregate replacement ratio and the relative variations can be seen in Fig. 4. Along with the absolute values we give the relative variations as a function of the FRA incorporation ratio (Δ_{FRA}) for a given superplasticizer and as a function of the superplasticizer used (Δ_{WS}) for each FRA incorporation value.

The reference mixes had splitting tensile strengths (f_{ctm}) of 2.9 MPa (no admixture), 3.7 MPa (SP 1) and 4.5 MPa (SP 2), which were reduced by up to 15.6%, 19.0% and 24.3% when FRA were incorporated. The addition of superplasticizers led to splitting tensile strength increases up to 26.6% and 52.8% when SP 1 and SP 2, respectively, were used. These gains are consistent with those reported elsewhere [13], showing that the use of superplasticizers can cancel out the negative effects of the FRA incorporation.

Good linear correlation was established between the relative tensile strength loss and the FRA/FNA replacement ratio in mixes without admixtures (Fig. 4). The mixes made with superplasticizers registered higher values but were more sensitive to FRA incorporation, even though correlations were not as conclusive. Comparison of the linear regression lines' slopes shows that the relative fall in the concrete's w/c ratio and consequent increase of the FRA content in the mixes have more influence on the splitting tensile strength than increasing the mix compacity does.

With the exception of the FRAC with 30% FRA, whose performance was anomalous, the relative gain in splitting tensile strength was almost identical for all FRACs no matter what the FRA ratio (between 15.3% and 21.5% for SP 1 and between 37.0% and 42.5% for SP 2), allowing the conclusion that the influence of the superplasticizer on this property (Fig. 5) is not influenced by FRA incorporation. The lesser influence of superplasticizers on FRAC can be linked to the increased specific surface of the FRA for the same superplasticizer content, thus reducing its efficiency. On the other hand, the fact that splitting tensile strength is less sensitive to w/c ratio reductions than compressive strength [47] may lead to greater influence on the concrete performance in the presence of FRA. In order to establish a correlation between compressive strength and splitting tensile strength, an Eq. (2) based on Model Code's recommendation [23] was conceived, in which not only the compressive strength was taken into account, but also the different densities of FNA and FRA (to take into consideration the replacement ratio) and the type of superplasticizer used, which influences the w/c ratio. The independent variables are the compressive strength (f_c), previously presented and discussed [33], the replacement ratio (r), and the effective water/cement ratio of the mix (w/c). The constants ρ_{FNA} and ρ_{FRA} are the saturated surface dry densities of FNA and FRA, respectively, and $(w/c)_{RC0}$ is the effective water/cement ratio of the reference concrete, made with no superplasticizers. Finally, a and b are correlation factors.

$$F_{ctm} = a \cdot f_c^{\frac{2}{3}} \cdot ((1-r) \cdot \rho_{FNA} + r \cdot \rho_{FRA}) \cdot \left[\frac{(W/C)_{RC0}}{(W/C)}\right]^b \quad (1)$$

Considering that for this specific case ρ_{FNA}, ρ_{FRA} and $(w/c)_{RC0}$ were 2.62 g/cm^3, 2.23 g/cm^3 and 0.55, respectively, correlation factors a and b are equal to 0.096 and 0.177, with a coefficient of determination R^2 = 0.927, which seems to prove that the approach taken is reasonable.

4.2. Modulus of elasticity

The results for the 28-day modulus of elasticity are given in Table 5. It contains both the absolute values and the relative varia-

Table 4
28-Day splitting tensile strength.

Superplasticizer	RC			C10			C30			C50			C100		
	f_{ctm} (MPa)	Δ_{FRA} (%)	Δ_{SP} (%)	f_{ctm} (MPa)	Δ_{FRA} (%)	Δ_{SP} (%)	f_{ctm} (MPa)	Δ_{FRA} (%)	Δ_{SP} (%)	f_{ctm} (MPa)	Δ_{FRA} (%)	Δ_{SP} (%)	f_{ctm} (MPa)	Δ_{FRA} (%)	Δ_{SP} (%)
WS	2.9	0.0	0.0	2.9	0.7	0.0	2.7	−6.7	0.0	2.6	−10.1	0.0	2.5	−15.6	0.0
SP 1	3.7	0.0	26.6	3.4	−8.3	15.3	3.3	−11.0	20.7	3.1	−16.5	17.6	3.0	−19.0	21.5
SP 2	4.5	0.0	52.8	4.2	−6.4	42.1	4.5	0.7	64.9	3.7	−16.7	41.6	3.4	−24.3	37.0

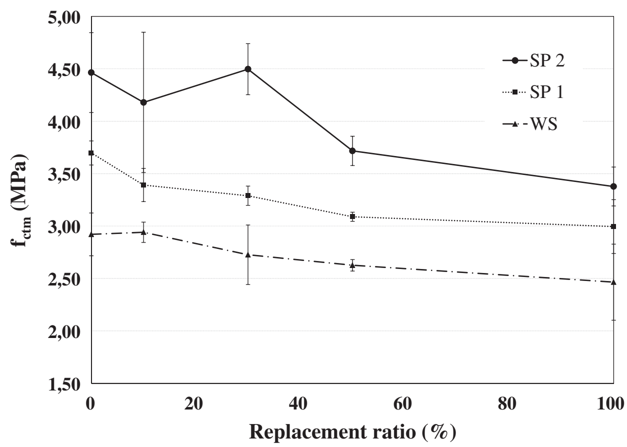

Fig. 3. Splitting tensile strength and FNA/FRA replacement ratio at 28 days.

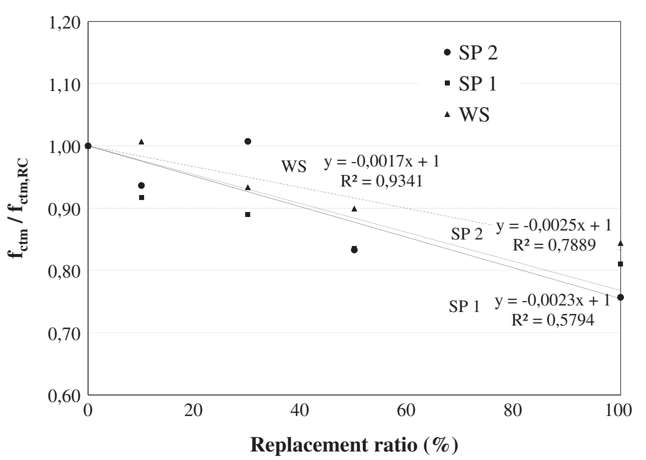

Fig. 4. FRAC relative 28-day splitting tensile strength and FNA/FRCA replacement ratio.

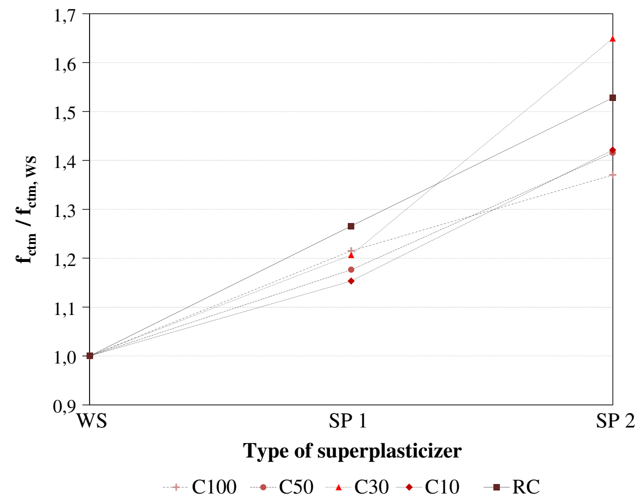

Fig. 5. FRAC relative 28-day splitting tensile strength and superplasticizer type.

tions as a function of the FRA incorporation ratio (Δ_{FRA}) for a given superplasticizer and as a function of the superplasticizer used (Δ_{WS}), for each FRA incorporation value.

A preliminary analysis shows that the absolute values are higher than expected, based on the CEB FIP Model Code [23]. However Tomosawa and Takafumi [48] presented new proposals to determine the value of the modulus of elasticity in high-performance concrete (f_{cm} > 40 MPa) that are within the range of those obtained in our study. Khatib [16] obtained values of the dynamic modulus of elasticity, roughly corresponding to the modulus of elasticity tangent at the origin of the axes, whose range is similar to that of the values obtained here, even though these two properties should not be compared directly.

In relative terms the use of superplasticizers significantly increased the modulus of elasticity value, even in FRAC, with improvements of up to 20.7% for SP 1 and 33.0% for SP 2 (Fig. 6). On the other hand, the replacement of FNA with FRA resulted in losses of up to 13.2% for mixes without admixture, 17.0% for SP 1 and 9.5% for SP 2.

The linear regressions established in Fig. 7 indicate that FRACs made with superplasticizers show sensitivity that is similar to but better than that of mixes without admixtures, and that FRACs with SP 2 show the best results for FRA incorporation.

It is concluded that for the mixes without admixtures there is a clear relationship between a decrease in the modulus of elasticity and FRA incorporation. The results for the mixes with SP 2 suggest that the influence of increased w/c ratio is lower than the effect of the increase in concrete compacity; but the mixes with SP 1 seem to indicate that the increase in the w/c ratio is the conditioning factor.

Mehta and Monteiro [49] described how the density of concrete is intrinsically related to its modulus of elasticity. Fig. 8 shows a very good correlation between these characteristics for the FRACs tested.

The analysis of the effect of superplasticizers on the evolution of the modulus of elasticity for each aggregate replacement ratio prescribed (Fig. 9) shows that superplasticizer SP 1 influences the mixes with lower FRA ratios more emphatically and loses efficiency for higher incorporations (even though C100 displays an intermediate performance). Mixes with SP 2 follow the same trend, but differences are less obvious. Whilst the higher specific surface of FRA may negatively influence mixes containing superplasticizers because the polymeric chains have a larger contact area, the steric effects produced in concrete made with polycarboxylic superplasticizers may mitigate the negative effect of incorporating FRA.

In order to correlate the modulus of elasticity with the compressive strength it is necessary to consider also the remaining aspects that influence the FRAC's performance: quality of FRA; replacement ratio; w/c ratio. Therefore, Eq. (2) was developed, based also on Model Code 90 [21], but considering these parameters as well:

Table 5
28-Day modulus of elasticity.

Superplasticizer	RC			C10			C30			C50			C100		
	E_{cm} (GPa)	Δ_{FRA} (%)	Δ_{SP} (%)	E_{cm} (GPa)	Δ_{FRA} (%)	Δ_{SP} (%)	E_{cm} (GPa)	Δ_{FRA} (%)	Δ_{SP} (%)	E_{cm} (GPa)	Δ_{FRA} (%)	Δ_{SP} (%)	E_{cm} (GPa)	Δ_{FRA} (%)	Δ_{SP} (%)
WS	34.4	0.0	0.0	33.7	−2.2	0.0	32.3	−6.2	0.0	32.3	−6.2	0.0	29.9	−13.2	0.0
SP1	41.3	0.0	20.0	40.6	−1.6	20.7	36.0	−12.8	11.5	35.0	−15.3	8.4	34.2	−17.1	14.6
SP2	43.9	0.0	27.6	43.9	0.0	30.4	41.9	−4.4	30.0	40.2	−8.5	24.5	39.7	−9.5	33.0

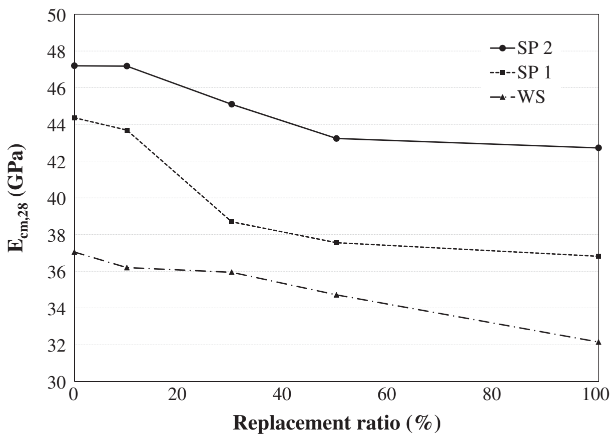

Fig. 6. Modulus of elasticity and FNA/FRA replacement ratio at 28 days.

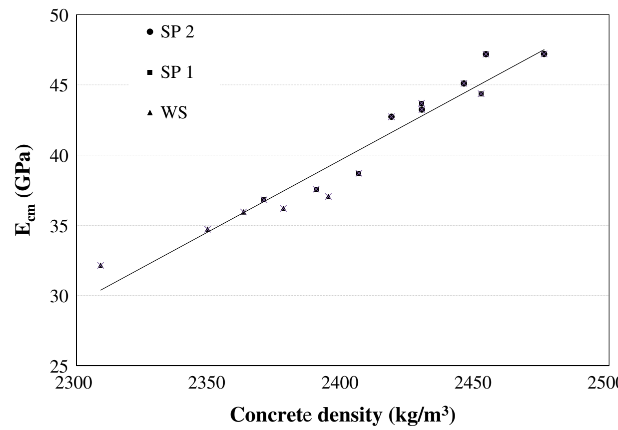

Fig. 8. Modulus of elasticity and concrete density.

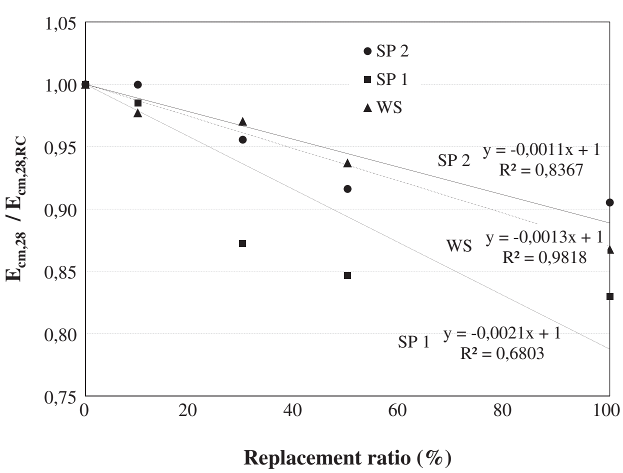

Fig. 7. FRAC relative 28-day modulus of elasticity and FNA/FRCA replacement ratio.

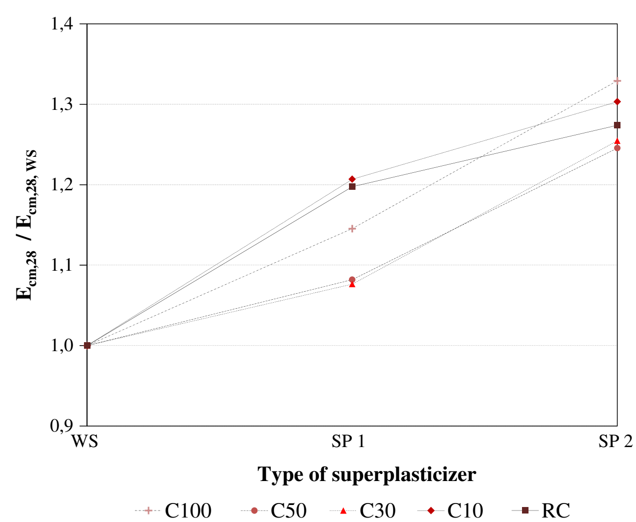

Fig. 9. FRAC relative 28-day modulus of elasticity and superplasticizer type.

$$E_{cm} = a \cdot f_c^{\frac{1}{3}} \cdot ((1-r) \cdot \rho_{FNA} + r \cdot \rho_{FRA}) \cdot \left[\frac{(W/C)_{RCO}}{(W/C)}\right]^b \qquad (2)$$

Given the variables and constants already discussed in Section 4.2, correlation factors take the values of 4.228 and 0.22, respectively, with a coefficient of determination $R^2 = 0.916$.

4.3. Abrasion resistance

The absolute results for wear resistance determined by the abrasion test are presented in Table 6 and, as with the previous tests, include the relative variations as a function of the FRA incorporation ratio (Δ_{FRA}) for a given superplasticizer and as a function of the superplasticizer used (Δ_{WS}), for each FRA incorporation value. The test revealed that FRA incorporation has an unfavourable influence on concrete performance (Fig. 10), the worst of all the FRAC mechanical properties evaluated here.

Increased wear of up to 217% (no admixture), 39.5% (SP 1) and 51.3% (SP 2) were found. The addition of superplasticizers led to increases in abrasion resistance of up to 23.7% and 33.2% for mixes with SP 1 and with SP 2. These results contradict those of Evangelista and de Brito [18] who found wear resistance gains in mixes with 100% FRA.

The effect of FRA is highlighted in Fig. 11 through the very stable trends established for mixes without superplasticizers and with SP 1, but not for mixes with SP 2. As Neville [30] and de Brito [22] have stated, this effect is associated with greater water w/c ratios, usual in FRACs, and with the greater porosity of the fines and binder paste, also caused by the FRA. Even though in absolute

Table 6
91-Day abrasion resistance.

Superplasticizer	RC			C10			C30			C50			C100		
	Δl (mm)	Δ_{FRA} (%)	Δ_{SP} (%)	Δl(mm)	Δ_{FRA} (%)	Δ_{SP} (%)	Δl (mm)	Δ_{FRA} (%)	Δ_{SP} (%)	Δl (mm)	Δ_{FRA} (%)	Δ_{SP} (%)	Δl (mm)	Δ_{FRA} (%)	Δ_{SP} (%)
WS	3.9	0.0	0.0	3.6	−6.2	0.0	4.4	12.7	0.0	4.6	17.7	0.0	4.7	21.7	0.0
SP 1	3.0	0.0	−23.7	3.3	9.9	−10.6	3.7	24.4	–	3.9	32.5	−14.1	4.1	39.5	–
SP 2	2.6	0.0	−33.2	3.2	22.7	−12.6	3.5	35.3	–	3.7	43.1	−18.7	3.9	51.3	–

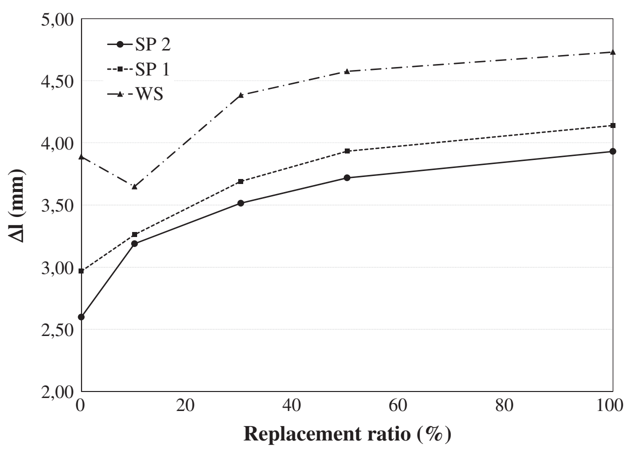

Fig. 10. Abrasion resistance (in terms of wear thickness *l*) and FNA/FRA replacement ratio at 28 days.

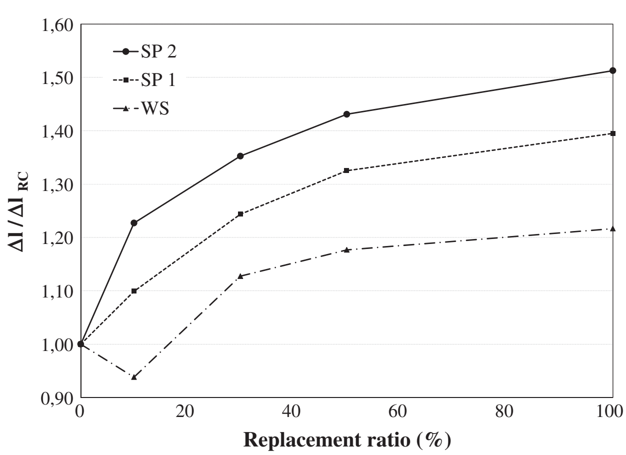

Fig. 11. FRAC relative abrasion resistance (in terms of wear thickness *l*) and FNA/FRCA replacement ratio.

terms the FRACs made with admixtures increased their abrasion resistance by comparison with the FRACs without them (Fig. 10), the relative reductions with the FRA incorporation ratio are greater. It is concluded that concrete abrasion resistance is more sensitive to FRA incorporation the greater the water reducing power of the superplasticizer used.

The analysis of the relative influence of the superplasticizers on the abrasion resistance of the RCs and the FRACs (Fig. 12) shows that it is greater on the former. The loss of efficiency may be related to the increase in the specific surface of the FRAs and of the effective w/c ratio of the FRACs.

4.4. Upgrading FRAC to RC performance

It has been explained above that FRACs generally have lower performance than the RCs. Eq. (3) provides the additional amount

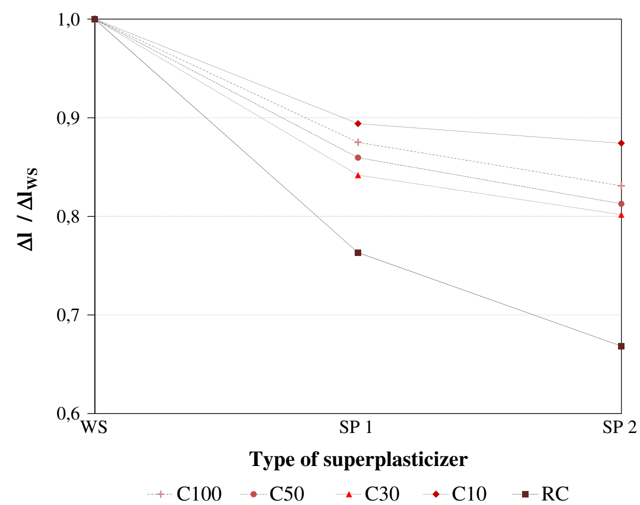

Fig. 12. FRAC relative 28-day relative abrasion resistance (in terms of wear thickness *l*) and superplasticizer type.

Table 7
Additional superplasticizer content in FRAC to equal RC's performance.

	RC0		RC1	RC2
	SP 1 (%)	SP 2 (%)	SP 1 (%)	SP 2 (%)
RC	0.00	0.00	0.00	0.00
C10	0.11	0.08	0.68	0.07
C30	0.35	0.11	0.72	0.13
C50	0.64	0.27	1.31	0.20
C100	0.86	0.50	1.32	0.32

of the superplasticizer as a percentage of the cement mass C (SP_i (%C)) needed for a concrete mix, with a given incorporation ratio of FRA k and made with admixture j, improve its performance concerning property i from $C_{j,k}$ to the corresponding level of the RC (RC_i). In this equation $C_{0,k}$ represents the performance concerning property i of a mix with the same FRA ratio k but no admixture. The value of SP_i (%C) to be adopted in design will be the highest of the values determined for the properties deemed conditioning in terms of the predicted use of the FRAC. In this equation it was assumed that all the mixes containing superplasticizers and produced in this experiment had an admixture content of 1% of the cement mass:

$$SP_i(\%C) = \frac{RC_i - C_{j,k}}{C_{j,k} - C_{0,k}} \times 1\% \quad (3)$$

This expression led to Table 7, which provides the additional amounts of superplasticizer (as a percentage of cement mass) needed as a function of the conditioning property of each FRAC. Abrasion resistance was not considered because it is unlikely that FRAC will be used in abrasive environments.

Expression (3) was simplified by considering that the effects of the superplasticizers on the various mechanical performances are proportional to their content, which is acceptable if only small variations are considered.

5. Conclusions

Some conclusions can be drawn from this experimental campaign concerning the effect of superplasticizers on concrete made with fine recycled aggregates (FRA). Several replacement ratios (ranging from 10% to 100%) were used and compared with reference concrete (RC), made solely with natural aggregates. FRACs show worse mechanical performances than the corresponding RCs. But it can be said that, in all the situations analysed, their quality was good enough for structural use. The following conclusions are based on the experimental results:

- There was a loss of splitting tensile strength (from 15.6% to 24.3%) with FRA incorporation either with superplasticizers or without them; FRAC with superplasticizers yield better absolute results (from 26.6% to 52.8%), even though within each concrete family studied (i.e. comparing the improvement in FRAC with that in RC) the admixtures' performance in FRAC is worse.
- The modulus of elasticity is also negatively influenced by FRA (reductions from 9.5% to 17%); in terms of improvement linked to the superplasticizers, mixes with SP 1 performed worse than those with SP 2 (20.7% against 33.0%) and the absolute values of the latter are also higher; in relative terms the efficiency in RC lies between those in FRAC with SP 1 and SP 2.
- Both splitting tensile strength and modulus of elasticity can be correlated with compressive strength, but only if additional parameters, such as replacement ratio and effective water cement ratio are also taken into account.
- Of all the mechanical characteristics tested (including compressive strength) abrasion resistance was the one that declined the most with FRA incorporation (between 21.7% and 51.3%); the greater the water reducing power of the admixture the worse the relative performance of FRA, and the greater the FRA ratio the less the resistance gain from using superplasticizers.
- With the exception of abrasion resistance it is predicted that small increments of the superplasticizer content and the reduction of the w/c ratio will make it possible to produce FRACs of the same or better performance than the corresponding RCs with no admixtures, with less efficient ones or with lower admixture content.

Further studies are needed to understand how superplasticizers can affect the durability performance of concrete made with fine recycled concrete aggregates and to compare it with their influence on the performance of concrete made with coarse concrete recycled aggregates, both in mechanical terms [50] and durability terms [51].

Acknowledgements

The authors gratefully acknowledge the support of the ICIST Research Institute, IST, Technical University of Lisbon and the FCT (Foundation for Science and Technology).

References

[1] Nixon P. Recycled concrete as an aggregate for concrete – a review. Mater Struct 1978;11:371–8.
[2] Hansen T. Recycling of demolished concrete and masonry, RILEM report 6. London, UK: E&FN Spon; 1992. 336p.
[3] Katz A. Treatments for the improvement of recycled aggregate. J Mater Civil Eng 2004;16(6):597–603.
[4] Kou SC, Poon CS, Agrela F. Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. Cem Concr Compos 2011;33(8):788–95.
[5] Katz A. Recycling of partially hydrated concrete. In: Wascon 2000 – international conference on the science and engineering of recycling for environmental protection. Harrogate, UK; 2000. p. 383–91.
[6] Sagoe-Crentsil KK, Brown T, Taylor AH. Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cem Concr Res May 2001;31(5):707–12.
[7] Rahal K. Mechanical properties of concrete with recycled coarse aggregate. Build Environ 2007;42(1):407–15.
[8] Corinaldesi V. Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. Construct Build Mater 2010;24(9):1616–20.
[9] Fonseca N, de Brito J, Evangelista L. The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. Cem Concr Compos 2011;33(6):637–43. http://dx.doi.org/10.1016/j.cemconcom.
[10] Amorim P, de Brito J, Evangelista L. Concrete made with coarse concrete aggregate: Influence of curing on durability. ACI Mater J 2012;109(2): 195–204.
[11] Grdic ZJ, Toplicic-Curcic GA, Despotovic IM, Ristic NS. Properties of self-compacting concrete prepared with coarse recycled concrete aggregate. Construct Build Mater 2010;24(7):1129–33.
[12] Kou SC, Poon CS. Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates. Cem Concr Compos 2009;31(9):622–7.
[13] Ajdukiewicz A, Kliszczewicz A. Influence of recycled aggregates on mechanical properties of HS/HPC. Cem Concr Compos 2002;24(2):269–79.
[14] Olorunsogo FT, Padayachee N. Performance of recycled aggregate concrete monitored by durability indexes. Cem Concr Res 2002;32(2):179–85.
[15] Zaharieva R, Buyle-Bodin F, Skoczylas F, Wirquin E. Assessment of the surface permeation properties of recycled aggregate concrete. Cem Concr Compos 2003;25(2):223–32.
[16] Khatib JM. Properties of concrete incorporating fine recycled aggregate. Cem Concr Res 2005;35(4):763–9.
[17] Kou SC, Poon CS. Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. Construct Build Mater 2009;23(8):2877–86.
[18] Evangelista L, de Brito J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cem Concr Compos 2007;29(5):397–401.
[19] Leite MB. Evaluation of the mechanical properties of concrete made with recycled aggregates from construction and demolition waste (in Portuguese). PhD thesis. Porto Alegre, Brazil: Federal University of Rio Grande do Sul; 2001. 270p.
[20] Evangelista L, de Brito J. Durability performance of concrete made with fine recycled concrete aggregates. Cem Concr Compos 2010;32(1):9–14.
[21] EuroLightCon. Tensile strength as design parameter – economic design and construction with light weight aggregate concrete. Document BE96-3942/R32. European Union – Brite EuRam III; June 2000.
[22] de Brito J. Recycled aggregates and their influence on concrete properties (in Portuguese). Lecture within the full professorship in civil engineering pre-admission examination. Technical University of Lisbon, Lisbon: Instituto Superior Técnico; 2005.
[23] CEB-FIP. Model Code 90. Thomas Telford; 1993. 437p.
[24] Solyman M. Classification of recycled sands and their applications as fine aggregates for concrete and bituminous mixtures. PhD thesis. Kassel, Germany: Fachbereich Bauingenieurwesen der Universität Kassel; 2005. 171p.
[25] Corinaldesi V, Moriconi G. Influence of mineral additions on the performance of 100% recycled aggregate concrete. Construct Build Mater 2009;23(8):2869–76.
[26] Liu TC. Abrasion resistance of concrete. J Am Concr Inst 1981;78(5):341–50.
[27] Dhir RK, Hewlett PC, Chan YN. Near-surface characteristics of concrete: abrasion resistance. Mater Struct 1991;24(2):122–8.
[28] Horszczaruk E. Abrasion resistance of high-strength concrete in hydraulic structures. Wear 2005;259(1–6):62–9.
[29] de Brito J, Alves F. Concrete with recycled aggregates: the Portuguese experimental research. Mater Struct 2010;43(1):35–51.
[30] Neville AM. Properties of concrete. Pitman Internacional Text. London, UK; 2002.
[31] Frommenwiler A. New generation of superplasticizers for high performance concrete (HPC). Switzerland: MBT Holding; 2003. p. 50–62.
[32] NP EN 933-1. Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution. Sieving method, IPQ, Lisbon, Portugal; 2000. 16p.
[33] Pereira P, Evangelista L, de Brito J. The influence of superplasticizers on the workability and compressive strength of concrete made with fine recycled concrete aggregates. Construct Build Mater 2012;28(1):722–9.
[34] NP EN 206-1: 2007. Concrete. Part 1: Specification, performance, production and conformity. IPQ, Lisbon, Portugal; 2010. 84p.
[35] NP EN 1097-6. Test for mechanical and physical properties of aggregates. Part 6: Determination of particle density and water absorption. IPQ, Lisbon, Portugal; 2003. 33p.
[36] NP EN 1097-3, Tests for mechanical and physical properties of aggregates. Part 3: Determination of loose bulk density and voids. IPQ, Lisbon, Portugal; 2002. 16p.
[37] NP EN 933-4. Tests for geometrical properties of aggregates. Part 4: Determination of particle shape. Shape index, IPQ, Lisbon, Portugal; 2008. 14p.
[38] NP EN 1097-2, Tests for mechanical and physical properties of aggregates. Part 2: Methods for the determination of resistance to fragmentation, IPQ, Lisbon, Portugal; 2000. 32p.
[39] Faury J-P, Le béton. 3rd éd.. Paris: Dunod; 1958.

[40] NP EN 12390-2. Testing hardened concrete. Part 2: Making and curing specimens for strength tests. IPQ, Lisbon, Portugal; 2009. 11p.
[41] NP EN 12390-6: 2009. Testing hardened concrete. Part 6: Tensile splitting strength of test specimens. IPQ, Lisbon, Portugal; 2009. 10p.
[42] Raphael JM. Tensile strength of concrete. ACI Struct J 1984;81(2):158–65.
[43] Oluokun FA. Prediction of concrete tensile strength from its compressive strength. ACI Mater J 1991;88(3):302–9.
[44] Zain MFM, Mahmud HB, Ilham A, Faizal M. Prediction of splitting tensile strength of high-performance concrete. Cem Concr Res 2002;32(8):1251–8.
[45] LNEC E397. Concrete: determination of the modulus of elasticity in compression. Lisbon, Portugal: National Laboratory of Civil Engineering; 1993. 8p.
[46] DIN 52108: 2010-05. Testing of inorganic non-metallic materials – Wear test using the grinding wheel according to Böhme – Grinding wheel method. Bleuth, Germany; 2010. 11p.
[47] Popovics S. Strength and related properties of concrete: a quantitative approach. John Wiley and Sons Inc.; 1998. 535p.
[48] Tomosawa F, Noguchi T. Relationship between compressive strength and modulus of elasticity of high-strength concrete. In: Third international symposium on utilization of high-strength concrete, vol. 2. Lillehammer, Norway; 1993. p. 1247–54.
[49] Mehta PK, Monteiro PJM. Concrete: microstructure properties and materials. 3rd ed. McGraw Hill; 2006. 659p.
[50] Matias D, de Brito J, Rosa A. Figueiredo C. Mechanical properties of concrete produced with recycled coarse aggregates – Influence of the use of superplasticizers. Cem Concr Compos submitted for publication.
[51] Matias D. de Brito J, Rosa A, Figueiredo C. Durability of concrete with recycled coarse aggregates: influence of superplasticizers. ACI Mater J, submitted for publication.