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Rheological behaviour of concrete made with fine recycled concrete aggregates – Influence of the superplasticizer

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HIGHLIGHTS

- The use of FRCA significantly increased the shrinkage and creep deformation.
- The FRCA's effect on rheological behaviour is influenced by the curing age.
- Superplasticizers increase early-age shrinkage but decrease it in the long-term.
- High-performance superplasticizer decreases creep deformation.
- The incorporation of FRCA partially hindered the effectiveness of the superplasticizers.

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ABSTRACT

This paper evaluates the influence of two superplasticizers (SP) on the rheological behaviour of concrete made with fine recycled concrete aggregates (FRCA). Three families of concrete were tested: family C0 made without SP, family C1 made with a regular superplasticizer and family C2 made with a high-performance superplasticizer. Five replacement ratios of natural sand by FRCA were tested: 0%, 10%, 30%, 50% and 100%. The coarse aggregates were natural gravels. Three criteria were established to design the concrete mixes' composition: keep the same particle size distribution curves, adjust the water/cement ratio to obtain a similar slump and no pre-saturation of the FRCA. All mixes had the same cement and SP content. The results show that the incorporation of FRCA significantly increased the shrinkage and creep deformation. The FRCA's effect was influenced by the curing age. The reference concrete made with natural sand stabilizes the creep deformation faster than the mixes made with FRCA. The incorporation of superplasticizer increased the shrinkage at early ages and decreased the shrinkage at 91 days of age. The regular superplasticizer did not improve the creep deformation while the high-performance superplasticizer highly improved this property. The incorporation of FRCA jeopardized the SP's effectiveness. This study demonstrated that to use FRCA and superplasticizer for concrete production it is necessary to take into account the different rheological behaviour of these mixes.

1. Introduction

The aggregates industry in the EU-27 plus EFTA countries comprises some 15,000 companies and 26,000 quarries and pits that employ around 238,000 workers. The production of aggregates in 2011 was estimated by the Aggregates European Association in 3 billion tonnes with an annual turnover of 20 billion €. The average aggregates demand in Europe is just under 5.8 tonnes per capita per year. These data show the great economic and environmental importance of this sector in the developed countries [1].

Abbreviations: CDW, construction and demolition waste; CNA, coarse natural aggregates; CRAC, coarse recycled aggregates concrete; CRCA, coarse recycled concrete aggregates; EFTA, European Free Trade Association; EU, European Union; FNA, fine natural aggregate; FRA, fine recycled aggregates; FRAC, fine recycled aggregates concrete; FRCA, fine recycled concrete aggregate; NA, natural aggregates; RA, recycled aggregates; RAC, recycled aggregates concrete; RC, reference concrete; RCA, recycled concrete aggregates; SCC, self compacting concrete; SP, superplasticizer; $(w/c)_{ef}$, effective water/cement ratio.

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The most common types of aggregates used in the construction sector are crushed rock from quarries (49%), natural gravel and sand from pits (41%), recycled aggregates from construction and demolition waste (CDW) (6%) and other such as marine aggregates, slag, bottom ash, fly ash, etc. (4%). Approximately 45% of the aggregates are consumed in the manufacture of concrete and mortar, 45% are used as unbound materials and the remaining 10% in asphalt concrete production [1].

Recycled aggregates from CDW are an alternative to natural aggregates, but the recycling rate varies greatly within the EU states. While countries like the Netherlands, Denmark, Germany, Ireland and United Kingdom have a recycling rate over 75%, others like Spain, Portugal and Italy have a recycling rate around 15–20%. The average recycling rate in the EU-27 was estimated at around 46% [2]. According to the Waste Framework Directive of the European Parliament on waste, a minimum of 70% by weight of non-hazardous CDW shall be prepared for re-use and recycling in 2020 [3], which highlights the need of these Southern European countries to achieve this rate.

In these Southern European countries the majority of recycled aggregates (RA) are used in road construction [4,5] and unpaved rural roads [6]. These uses have little added value but are a good alternative for RA with medium or low quality [7]. Using selective demolition techniques, RA of high quality with a high potential for recycling can be obtained [8]. The use of these high-quality aggregates in the manufacture of concrete and mortar gives more added value to these recycled materials. Hence, numerous researchers have been conducted in the last two decades to evaluate the performance of concrete and mortar made with RA. Most have focused on the use of RCA, since concrete represents 30% or 40% by weight of the total CDW generated in the EU [2].

Recycled concrete aggregates (RCA) are composed of NA with approximately 30% of adhered mortar [9]. The adhered mortar give the RCA a rough surface with numerous pores and micro-cracks [10], which justify the main characteristics of RCA: more porosity, much higher water absorption, lower density and greater angularity and irregular shape [11,12].

Two fractions of RCA have been used by researchers in the manufacture of concrete: coarse recycled concrete aggregates (CRCA) for replacement gravels; and fine recycled concrete aggregates (FRCA) for replacement natural sand. The fine fraction has also been used in the manufacture of mortar [13,14].

The incorporation of CRCA significantly affects fresh concrete's density and workability [15]. Generally, the mechanical properties decrease as the CRCA ratio increases [16]. The incorporation of CRCA has a detrimental effect on shrinkage deformation [17]. The creep deformation of concrete increases with the incorporation of CRCA, due to the lower modulus of elasticity of CRAC caused by their lower stiffness [18]. The shrinkage and creep deformations cause internal strength, hence they have to be considered as fundamental properties of structural concrete. These deformations can cause the occurrence of cracks that compromise the durability of a structure. In durability-related terms, CRAC showed higher water absorption by immersion and capillarity [19]. The chloride penetration resistance and carbonation resistance decrease with the incorporation of CRCA [20].

Fewer studies on the use of FRCA have been carried out by researchers. This fraction shows worse physico-mechanical and chemical properties, such as greater amount of cement paste, porosity, water absorption and acid soluble sulphate content, which may limit its use in concrete [21]. The incorporation of FRCA reduces mechanical strength, increases shrinkage and has a negative effect on the durability behaviour of RCA [22–23]. For these reasons many codes allow the incorporation of CRCA in structural concrete but do not allow replacing FNA by FRCA in structural concrete production. Gonçalves and de Brito [24] made an extensive revision of the current standards that allow the use of RCA and of its restrictions.

Evangelista and de Brito [25] made an extensive state of the art on the use of FRCA in concrete production and concluded that it is possible to replace FNA by FRCA, provided that the properties of the recycled aggregates are taken into account in the mix design and production. Nevertheless, these authors concluded that there are some properties that need further investigation, such as the durability and rheological properties. They also highlighted the need to define the constitutive equations of concrete made with FRCA.

The use of SP reduces the mixing water maintaining the workability, which for the same cement content allows reducing the (w/c) ratio and improves the mechanical and durability properties of RCA [26–28].

To determine the effect of regular superplasticizer and high-performance superplasticizer on concrete's performance, an extensive study had been carried out at IST in Lisbon. This paper presents the influence of both kinds of superplasticizer on the rheological properties of concrete made with FRCA. From a theoretical point of view, rheology is the relationship between loading and deformation behaviour of materials that cannot be described by classical mechanics or elasticity. One of the major tasks of rheology is to empirically establish the relationships between deformations (or rates of deformation) and stresses, which has been addressed in this study. To the best of the authors' knowledge there are no other studies on the effect of superplasticizer on the rheological behaviour of structural concrete made with FRCA. This study follows another one of the same authors on the durability of concrete with FRCA and SP [29] and promotes its use in concrete production in order to reduce the consumption of non-renewable natural resources such as sand from river bank or crushed natural rock from quarries. This study also contributes to preventing the accumulation of the FRCA in landfills.

2. Literature review

This section is focused on the rheological behaviour of concrete made with FRCA, specifically on the shrinkage and creep deformation, and presents chronologically the studies published in the last decade that have been the basis of this work.

Khatib [30] examined the influence of replacing FNA by FRCA on the shrinkage. FRCA with particle size less than 5 mm was used and five replacement ratios by weight were tested: 0%, 25%, 50%, 75% and 100%. No data on the source concrete were available. A free water/cement ratio of 0.5 was used in all mixes. No superplasticizers were used. An increase in the slump was observed with the increase in FRCA content. The incorporation of FRCA caused a linear increase in shrinkage deformation.

Kou and Poon [31] used the same replacement ratios as Khatib [30]. In a first series the authors maintained a constant free water/cement of 0.53 in all mixes. The slump increased with the incorporation of FRCA, which was attributed to the greater amount of free water in the mix. The incorporation of FRCA had a detrimental effect on the drying shrinkage. At 112 days an increase of 26% was observed for the 100% replacement ratio relative to the RC. In a second series, water was added to obtain a slump of 60–80 mm in all mixes. In this case the drying shrinkage in the mix with 100% replacement ratio was higher by 22% than that of the RC.

Kou and Poon [32] in a second study showed the results of three series of SCC. In series I the FRCA were used as 0%, 25%, 50%, 75% and 100% by volume replacements of FNA. A constant w/c ratio of 0.53 was used. In series II fine fly ash was added to increase the cementitious materials content. The same replacement ratios of FNA by FRCA were tested with a constant w/c ratio of 0.44. In series III three w/c ratios of 0.44, 0.40 and 0.35 were used in mixes with 100% replacement ratio. The incorporation of 100% FRCA resulted in an increase of the drying shrinkage of 111% and 96% (relative to the RC) in series I and II respectively. The results of series III showed that the drying shrinkage can be controlled by decreasing the w/c ratio. It was found that reducing the w/c ratio from 0.44 to 0.35 resulted in an improvement of 40% at 112 days.

Zega and Di Maio [33] studied the drying shrinkage of concrete made with up to 30% of FRCA. A constant w/c ratio of 0.45 and varying water-reducing admixture contents were used. These authors concluded that concretes with similar w/c ratio and aggregate volume have similar drying shrinkage after 180 days.

Evangelista and Brito [25] collected the conclusions of several theses, dissertations and conference papers, listed below. Regarding shrinkage, Merlet and Pimienta [34] evaluated the shrinkage of various concrete mixes with FRCA and concluded that the use of superplasticizer improved the mixes' shrinkage. Dillman [35] concluded that the shrinkage of mixes with 100% CRCA and up to 50% FRCA was comparable to that of RC. Solyman [36] found that the shrinkage of concrete mixes with FRCA was 15% higher than RC. Jeong [37] found that the increase in shrinkage due to the FRCA incorporation can be mitigated by replacing cement with fly ash. Regarding creep deformation, Ajdukiewicz and Kliszczewicz [23] concluded that the incorporation of FRCA harms the performance of RCA. Fraaij et al. [38] evaluated the creep of concrete made with total replacement ratio of CNA by CRCA and 50% replacement ratio of FNA by FRCA and found that the presence of RA strongly influences concrete's creep.

Domingo-Cabo et al. [39] made recycled concrete with 40 MPa of compressive strength replacing 0%, 20%, 50% and 100% of CNA by CRCA of good quality. They concluded that if the effective water–cement ratio was maintained constant, the compressive strength mean values were similar. In order to maintain the workability, the content of superplasticizer was doubled in the mix with 100% CRCA. The creep deformation of CRCA for a period of 180 days was 35%, 42% and 51% higher than the reference concrete for the 20%, 50% and 100% of replacement ratio respectively. The CEB-FIF models was that the best to predict the deferred deformation in the recycled concrete with replacement ratios higher than 20%. The shrinkage after a period of 180 days was around 20% and 70% higher than that of the reference concrete in recycled concrete with 50% and 100% of replacement ratios respectively.

Fathifazl et al. [40] proposed an Equivalent Mortar Volume (EMV) method taking into account the residual mortar and natural aggregate of RCA to improve the creep and shrinkage behaviour of concrete made with CRCA. The CRAC mixes proportioned by the EMV method experimented lower or comparable creep and shrinkage than RC, while the CRAC mixes proportioned by the conventional method always showed higher creep and shrinkage than RC. These results were attributed to the fact that the total mortar content of mixes made with RCA and NA proportioned by the EMV method was the same. These authors demonstrated that the greater mortar content of RCA was responsible for the higher creep in mixes prepared with a conventional method.

Manzi et al. [41] studied the effect of FRCA and CRCA on the short and long-term behaviour of structural concrete. These authors tested partial replacement ratios of natural sand (0/6 mm) and fine natural gravel (6/16 mm) by good quality RCA (0/16) and RCA (16/25 mm) coming from the demolished structure of a building 15 year old and with a 35 MPa f_{cm} concrete. CEM II-A/LL 42.5 R and a constant w/c ratio of 0.48 were used. The authors concluded that a proper assortment of FRCA and CRCA can lead to good structural concrete from a mechanical point of view. Regarding the shrinkage behaviour, all mixes showed similar shrinkage curves, with a rapid increase in the first 3 months, and decreases of slope of the curves over time, becoming almost flat after 10 months. RAC showed higher shrinkage than RC, which was attributed to the RCA offering less restraint to the potential shrinkage of the cement paste. Moreover, the creep phenomenon was still quite active after 1 year, the slope of the specific creep curves were significant in all mixes even after this time. The incorporation of RCA (0/16 mm) characterised by high water absorption led to the highest creep deformation.

The cracking behaviour of concrete made with FRCA is determined by its autogenous shrinkage and tensile creep. Ji et al. [42] studied the effect of the moisture state (oven-dried, air-dried and saturated surface-dried) of FRCA on the cracking susceptibility of concrete made with 50% of FRCA and 50% of natural fine aggregates. The authors concluded that a higher pre-wetting degree of FRCA may lead to the smaller autogenous deformation. However, the tensile creep mechanism of concrete made with FRCA with different moisture levels is not clear, so more autogenous shrinkage and creep tests are needed to understand the cracking mechanism of concrete made with FRCA.

3. Experimental programme

To study the influence of superplasticizers on the rheological behaviour of concrete made with CNA, three FRAC families and five replacement ratios of FNA by FRCA were tested: Family C0 was made without SP, family C1 was made with a regular superplasticizer chemically based on organic polymers and admixtures that works by electrostatic repulsion (SP1) and family C2 was made with a high-performance superplasticizer chemically based on a combination of modified polycarboxylates in an aqueous solution that works by electrostatic and steric repulsions (SP2).

A total of 15 concrete mixes were made. The label of each of mix includes the family number and the replacement ratio: Ci.X where $i = 0$, 1, and 2 and $X = 0\%$, 10%, 30%, 50%, and 100%.

3.1. Materials

Four commercial natural siliceous aggregates were used to make the RC: fine sand - 0/2 mm (FNA-1), coarse sand - 0/4 mm (FNA-2), medium gravel - 6/12 mm (CNA-1) and coarse gravel - 12/20 mm (CNA-2).

Since the mechanical and durability properties of RAC are related to the strength of the source concretes [43], the first step was to design and procure from a ready-mixed concrete company (Unibetão S.A.) a source concrete type X0 (P) CL0.40 D_{max} 22 S2 (C30/37 according to NP EN 206-1:2007). After 30 days of curing, blocks of this source concrete were crushed using a jaw crusher at the Construction Laboratory of IST. The crushed material was sieved to obtain the FRCA - 0/4 mm used in this study. This procedure has already been used by the authors in previous works [26,27].

Tables 1 and 2 show the particle size distribution and the physico-mechanical properties of the NA and the FRCA respectively. Due to the lower density of the adhered cement paste of the RA, the oven-dry particles density of the FRCA was around 14% lower than those of the FNA-1 and FNA-2, while the saturated surface-dry density of the FRCA was 8% lower. This is explained by the greater amount

Table 1
Particle size distribution.

Sieve size (mm)	Particles passing (%)					
	FNA-1	FNA-2	CNA-1	CNA-2	FRCA[a]	FAURY
31.5	100.00	100.00	100.00	100.00	100.00	100.00
22.4	100.00	100.00	100.00	99.50	100.00	100.00
16	100.00	100.00	99.70	67.30	100.00	84.77
11.2	100.00	100.00	90.70	8.50	100.00	69.70
8	100.00	99.90	35.70	1.50	100.00	62.67
5.6	100.00	98.70	4.40	0.70	100.00	55.71
4	100.00	96.40	0.70	0.60	100.00	49.59
2	100.00	76.40	0.30	0.50	62.95	38.21
1	98.80	27.50	0.30	0.40	41.23	28.30
0.5	75.30	7.30	0.20	0.40	20.33	19.68
0.25	20.90	3.50	0.20	0.40	9.47	12.17
0.125	4.50	1.80	0.20	0.20	3.34	5.63
0.0625	0.30	0.50	0.10	0.10	0.84	0.00
0	0.30	0.20	0.00	0.10	0.00	0.00
Fineness modulus	2.01	3.87	6.63	7.29	3.63	5.06

[a] Fraction 0/4 mm.

Table 2
Physico-mechanical properties of natural and recycled aggregates.

	D_{max} (mm)	Oven-dry particles density (ρ_{rd} (kg/m^3))	Saturated surface-dry particles density (ρ_{ssd} (kg/m^3))	Loose bulk density (kg/m^3)	Voids content (%)	Water absorption (WA_{24} (%))	Shape index (%)	Los Angeles coefficient (%)
Standard	EN 933-2:1999	EN 1097-6:2003	EN 1097-6:2003	EN 1097-6:2003	EN 1097-6:2003	EN 1097-6:2003	EN 933-4:2002	EN 1097-2:2002
FRCA[a]	4	2298	2460	1393	39.4	7.09	–	
FNA-1	1	2674	2678	1583	40.8	0.15	–	–
FNA-2	4	2667	2674	1542	42.2	0.26	–	–
CNA-1	11.2	2570	2600	1362	47	1.17	17.4	27.2
CNA-2	22.4	2639	2665	1370	48.1	0.98	15.7	25.6

[a] Fraction 0/4 mm.

of porous accessible to water of the RA. The same happens with the loose bulk density, although the voids content of the FRCA was lower than that of the NA. This is due to the more continuous particle size distribution of RA leading to higher compacity [6,7]. The FRCA's water absorption was 46% and 26% higher than that of the FNA-1 and FNA-2, respectively. The high water absorption of the FRCA requires that the water absorbed by these aggregates is compensated by extra water during the mixing process.

The SP-1 and SP-2 superplasticizers meet the technical specifications regulated by the NP-EN 934-2:2009. Its properties were described by Barbudo et al. [28] in a previous article. A cement CEM-I 42.5 R was used.

3.2. Concrete mixes' composition

Three criteria were established to design the concrete mixes' composition: (a) maintain the particle size distribution of the aggregates in all mixes; (b) guarantee a constant slump range of 125 ± 15 mm (using the Abram cone); and (c) mix the aggregates with its natural moisture – not pre-saturated.

Based on Faury's method [44] a reference concrete (C0.0) made with NA and no superplasticizer was designed. The following conditions were established: exposure class XC3, strength class C 25/30, slump class S3 (100–150 mm) and CEM-I 42.5 R (NP EN 206-1:2007).

To obtain the maximum compacity curve, the FRCA, FNA-1 and FNA-2 were sieved and separated in the following particle sizes: 0.063 mm, 0.125 mm, 0.25 mm, 0.5 mm, 1 mm, 2 mm and 4 mm. The mass of each of these fractions was calculated to achieve a perfect fit to the Faury's curve. FNA-1 and FNA-2 were replaced by FRCA by volume for each of the size fractions according to the following expression:

$$M_{FRCA} = \%i \times M_{FNA} \times \frac{\delta_{FRCA}}{\delta_{FNA}}$$

where:

- M_{FRCA} – mass of FRCA (kg).
- M_{FNA} – mass of FNA (kg).
- $\%i$ – FRCA incorporation ratio (%).
- δ_{AFRB} – oven-dry density FRCA (kg/dm^3).
- δ_{AFN} – oven-dry density FNA (kg/dm^3).

A fixed proportion of 1% of cement mass was used for both superplasticizers (SP-1 and SP-2) in all mixes. The mass of water to obtain the target slump was calculated taking into account the aggregates' water absorption over time. To avoid excess of free water not absorbed by the aggregates, the FRCA's water absorption evolution was determined following the methodology described by Leite [45]. The FRCA absorbed 77.4% of its potential capacity in the first 10 min (Fig. 1), i.e. the duration of the mixing process.

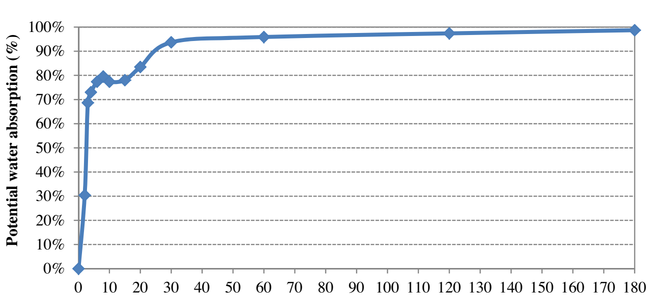

Fig. 1. FRCA's water absorption over time.

Two methods have been used in the literature to compensate the higher RCA's water absorption in the manufacture of RAC: to pre-saturate the aggregates before the mixing process or to add the extra water during the mixing process.

Pre-saturating the RCA reduces the water exchange between the RCA and the cement paste and it was suggested by many researchers. Barra and Vázquez [46] and Poon et al. [9] suggested that the saturation point should not be reached because of the risk of the later transfer of water from within the aggregates to the cement paste. Such transfer would modify the w/c ratio in the interfacial transition zone (ITZ) between RCA and the cement paste, affecting the bond strength. Barra and Vázquez [46] stated that concrete with air-dried RCA (at approximately 90% of potential water content) presented better results than concrete made with saturated surfaced dried RCA. Poon et al. [9] also obtained the best results in concrete made with air dried RCA (at approximately 50% of potential water content). Tam et al. [47] experimented a two-stage mixing, the pre-saturation of the RCA resulted in higher compressive strength concretes. Etxeberria et al. [48] recommended an 80% pre-saturation in RCA.

Cortas et al. [49] studied the effect of the water saturation of aggregates on the development of shrinkage and the potential cracking risk of early age conventional concrete. Initially dry aggregates (saturated at 0%) resulted in higher macro porosity and lower strength. Concrete made of saturated aggregates (saturated at 100%) showed higher meso porosity and lower strength than partially saturated aggregates (saturated at 50%). Concrete with initially saturated aggregates showed the highest potential risk of cracking,

Ferreira et al. [50] concluded that concrete made using the pre-saturation method exhibited slightly worse fresh and hardened properties than mixes made with the mixing water compensation method, although the differences were not significant for commercial large-scale production. Silva et al. [17] concluded that it is possible to control shrinkage of RAC by simply using a different mixing procedure; using a water compensation method, shrinkage strain can be reduced by as much as 30%, when compared to mixes made with pre-saturated RA.

In this study the FRCA was inserted in the mixer with its natural moisture (3.2%). Table 3 shows the detailed aggregate mass by particle size fractions to produce one cubic meter of concrete, as well as the w/c ratio and effective w/c ratio and slump achieved in all mixes. The mixing process is explained graphically in Fig. 2.

3.3. Specimen preparation and testing procedures

The evaluation of the fresh concrete properties is fundamental since they have a significantly impact on the shrinkage and creep of hardened concrete. Two properties were tested in the fresh state: slump (using the Abram cone) and density. The procedures described in the NP EN 12350-2:2009 and NP EN 12350-6:2009 were followed. The slump using the Abram cone was performed immediately after mixing ended.

To characterise the mechanical properties of hardened concrete, compressive strength was measured according to NP EN 12390-3:2009. For this purpose cubic specimens of 150 mm × 150 mm × 150 mm were used. The specimens were cured for 7, 28 and 56 days in a humidity chamber (chamber-1) programmed to maintain a temperature of 20 ± 2 °C and a relative humidity of 95 ± 5%. Three specimens were used per mix.

The shrinkage was measured according to specification LNEC E398-1993. Two specimens of 100 × 100 × 450 mm per mix were measured up to the age of 91 days. The specimen were demoulded 24 h after casting and cured in a dry chamber under controlled conditions (chamber-2): temperature of 20 ± 2 °C and relative humidity of 50 ± 5%. Measurements were taken daily for the first 8 days, then reduced gradually.

Using deflectometer readings, the shrinkage deformation of the specimen at any time t was calculates using the following expression:

$$\varepsilon_s(t) = \frac{d_i - d_0}{d}$$

where d_0 is the initial deflectometer reading ($t = 0$), d_i is the deflectometer reading at time (t) and d is the patter length between the marks embedded in the specimens.

Table 3
Composition of the concrete mixes.

	C0.0	C0.10	C0.30	C0.50	C0.100	C1.0	C1.10	C1.30	C1.50	C1.100	C2.0	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)	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0
Water (l)	178.5	183.6	186.7	193.6	209.9	150.5	159.1	169.3	179.4	192.9	133.0	138.0	141.5	148.3	160.8
w/c ratio[a]	0.51	0.52	0.53	0.55	0.60	0.43	0.45	0.48	0.51	0.55	0.38	0.39	0.40	0.42	0.46
$(w/c)_{ef}$ ratio[b]	0.51	0.52	0.52	0.53	0.55	0.43	0.45	0.47	0.49	0.50	0.38	0.39	0.39	0.40	0.41
FNA (kg) Total	900.8	806.6	626.5	446.2	0.0	942.6	840.3	646.2	455.8	0.0	969.7	862.9	676.0	480.2	0.0
0.063–0.125 (mm)	49.2	42.8	35.1	22.7	0.0	61.3	52.9	38.1	25.9	0.0	68.8	59.9	47.3	33.0	0.0
0.125–0.25 (mm)	116.8	104.1	81.5	58.8	0.0	120.6	107.6	83.3	58.7	0.0	124.1	111.2	86.0	61.2	0.0
0.25–0.500 (mm)	134.2	121.0	93.5	66.5	0.0	138.4	123.6	96.2	67.9	0.0	141.6	126.9	98.8	70.3	0.0
0.5–1.0 (mm)	154.1	138.6	107.2	76.2	0.0	159.4	142.0	109.4	77.7	0.0	162.9	140.2	113.5	80.8	0.0
1.0–2.0 (mm)	177.1	158.9	121.6	87.8	0.0	184.7	164.6	126.8	89.3	0.0	187.1	164.2	130.4	92.8	0.0
2.0–4.0 (mm)	269.4	241.3	187.6	134.2	0.0	278.2	249.5	192.4	136.3	0.0	285.2	260.6	199.9	142.1	0.0
FRCA (kg) Total	0.0	77.1	231.1	384.0	757.7	0.0	80.3	238.3	392.2	780.2	0.0	82.9	249.3	413.2	820.4
0.063–0.125 (mm)	0.0	4.1	12.9	19.6	37.2	0.0	5.1	14.0	22.3	43.7	0.0	5.7	17.4	28.4	55.5
0.125–0.25 (mm)	0.0	10.0	30.1	50.6	98.5	0.0	10.3	30.7	50.5	101.0	0.0	10.6	31.7	52.7	104.9
0.25–0.500 (mm)	0.0	11.6	34.5	57.2	113.7	0.0	11.8	35.5	58.4	116.0	0.0	12.1	36.5	60.5	120.5
0.5–1.0 (mm)	0.0	13.3	39.5	65.6	130.2	0.0	13.6	40.3	66.9	133.2	0.0	13.8	41.9	69.5	138.4
1.0–2.0 (mm)	0.0	15.2	44.8	75.5	149.2	0.0	15.7	46.8	76.8	153.0	0.0	15.7	48.1	79.8	159.0
2.0–4.0 (mm)	0.0	23.1	69.2	115.5	228.9	0.0	23.9	71.0	117.3	233.4	0.0	24.9	73.7	122.3	242.1
CNA-1 (kg)	237.0	236.0	236.0	235.0	233.0	246.0	243.0	241.0	239.0	238.0	251.0	248.0	248.0	248.0	247.0
CNA-2 (kg)	690.0	688.0	688.0	684.0	678.0	714.0	709.0	702.0	696.0	694.0	730.0	727.0	727.0	724.0	721.0
Superplasticizer (kg)	0.0	0.0	0.0	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)	122.5	126.0	122.0	129.5	125.5	122.0	129.5	125.0	122.5	119.0	123.5	126.0	127.5	126.0	137.0

[a] w/c ratio: total water in the mix/cement content;
[b] $(w/c)_{ef}$ ratio: total water in the mix discounting the water absorbed by the FRCA in 10 min.

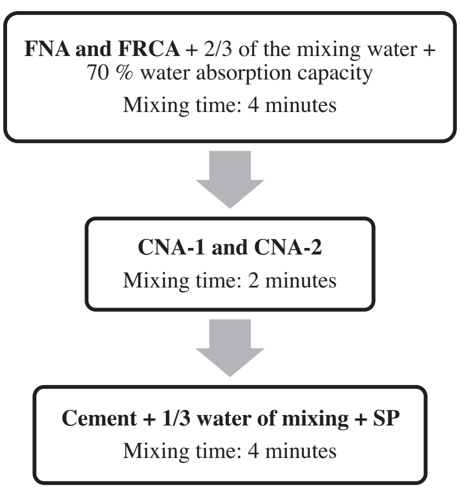

Fig. 2. Diagram of the mixing process.

The creep tests were carried out according to the procedures proposed in specification LNEC E399-1993. Only the reference concrete (C0.0) and the mixes with 100% replacement ratio (C0.100; C1.100 and C2.100) were tested. Two specimens of 100 × 100 × 450 mm per mix were monitored. The specimens were cured under the same climatic conditions as the specimens used for shrinkage: temperature of 20 ± 2 °C and relative humidity of 50 ± 5%. The tests began at the same age as the shrinkage tests, i.e. 1 day after casting. The creep deformations were measured at 91 days, coinciding with the days of the measurements of shrinkage.

The equipment used to perform the creep tests can apply a load of 100 kN uniformly distributed at the ends of the specimens. The stress on the loaded specimens is kept constant through hydraulic jacks connected to a hydraulic pump and an electronic device that allows controlling the oil injection at constant pressure within the hydraulic circuit. The deformation of the specimens is measured by precision electronic extensometers with a precision of microns.

The creep specimens were loaded initially ($t = 0$) to 20% of the maximum load and the first reading in length was made [$d_t(0)$]. Then they were loaded to apply a maximum stress of 10 MPa. This stress was greater than 50% of its compressive strength.

The creep deformation $\varepsilon_c(t)$ at any time was calculated using the following expression:

$$\varepsilon_c(t) = \varepsilon_t(t) - \varepsilon_s(t) - \varepsilon_i$$

where $\varepsilon_t(t)$ is the total deformation of the loaded specimen at time (t) calculated as follows:

$$\varepsilon_t(t) = \frac{d_t(i) - d_t(0)}{d} \times 100$$

where $d_t(0)$ is the length between two reference points embedded in the specimen at time $t = 0$ (mm), $d_t(i)$ is the length between these reference points at time $t = i$ (mm) and d is the pattern length measured between the attachment points of the electronic extensometer (mm). $\varepsilon_s(t)$ is the deformation due to the shrinkage at time (t) and ε_i is the instantaneous deformation due to load application calculated as follows:

$$\varepsilon_i = \frac{\sigma}{E}$$

where σ is the maximum stress applied in the creep test (10 MPa) and E is the modulus of elasticity calculated according to standard LNEC E397.

The creep coefficient $\varphi(t)$ was calculated using the following equation:

$$\varphi(t) = \frac{\varepsilon_c(t) \times Ec_{28d}}{\sigma(t)}$$

where Ec_{28d} is the modulus of elasticity at 28 days and $\sigma(t)$ is the applied stress at time (t).

The specific creep deformation $\varepsilon_{sp}(t)$ at any time t was calculated dividing the creep deformation at any time t by the stress applied on the specimen.

$$\varepsilon_{sp}(t) = \frac{\varepsilon_c(t)}{\sigma(t)}$$

4. Results and discussion

4.1. Workability

Table 3 presents the $(w/c)_{ef}$ of each mix necessary to achieve a slump in the Abrams cone of 125 ± 15 mm. The $(w/c)_{ef}$ was calculated with the total amount of water discounting the estimated water absorbed in 10 min by the FRCA. Mixes made with SP1 and SP2 require less water to obtain the target slump. Concrete mixes C1.0 and C2.0 reduced the $(w/c)_{ef}$ by 15.7% and 25.5% relative to C0.0. In mixes with 100% of FRCA, the incorporation of SP1 and SP2 reduced the $(w/c)_{ef}$ by 9.1% (C1.100) and 25.4% (C2.100) relative to C0.100. Similar results were obtained by Pereira et al. [26,27], who found decreases between 11% and 18% in concrete mixes made with SP1 and between 26% and 31% in concrete mixes made with SP2.

Concrete families C1.X and C2.X have lower $(w/c)_{ef}$ than C0.X and ii) $(w/c)_{ef}$ increases linearly with the incorporation of FRCA in the three concrete families. Mixes with 100% of FRCA showed an increase in $(w/c)_{ef}$ of 7.8% (C0.100), 16.3% (C1.100) and 7.9% (C2.100) relative to Ci.0. This was due to the shape of these recycled aggregates that increases the internal friction and consistency of the mix.

In relative terms, family C1 was more sensitive to the incorporation of FRCA than families C0 and C2. This is interpreted as a loss of effectiveness of SP1 with the incorporation of FRCA. Pereira et al. [26] found similar results. These authors explained this loss of effectiveness because the electrostatic repulsions of SP1 act on the surface of the aggregates. As the FRCA's specific surface area increases, for the same content of superplasticizer, the effectiveness will decrease. Conversely, the steric hindrance effects of SP2 were less affected by the surface area of the FRCA.

4.2. Fresh-state density

The density of fresh concrete depends on the weighted density of its components. Fig. 3 shows that the incorporation of superplasticizers increases the fresh density of the mixes. Concrete mixes C1.0 and C2.0 increased the fresh density by 2.8% and 2.7% relative to C0.0. The incorporation of SP1 and SP2 in mixes with 100% FRCA increased the fresh density relative to the C0 family by a similar value of 2.3% for the C1 and C2 families. These results are justified by the lower $(w/c)_{ef}$ of the mixes made with superplasticizers, the higher density of aggregates and the lower density of water relative to these materials.

The fresh concrete density also decreases with the incorporation of FRCA (Fig. 3). Mixes with 100% FRCA had a decrease of the fresh density of 3.3% (C0.100) and 3.7% (C1.100 and C2.100) relative to Ci.0. These results are justified by the lower density of FRCA. The density of mix C2.100 was only 1.1% lower than that of the reference concrete (C0.0).

In relative terms, the incorporation of FRCA affected in a similar manner the C0 and C2 families, while C1 family was slightly more affected (Fig. 4). This was justified by the lower effectiveness of SP1 to reduce the $(w/c)_{ef}$ in the presence of FRCA. The results agree with most of the authors that found linear decreases of concrete's fresh density as the incorporation of FRA increased [22,31–32].

4.3. Compressive strength

The compressive strength values at 7, 28 and 56 days is presented in Figs. 5–7 respectively. For all ages, an increase in the compressive strength values can be observed with the incorporation of SP. This was explained by the lower $(w/c)_{ef}$ in C1 and C2 concrete families and the higher density obtained with the use of

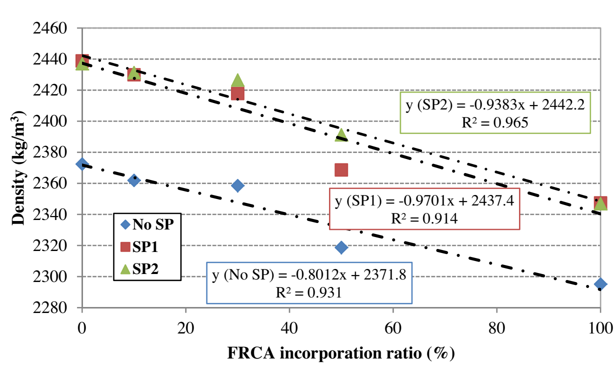

Fig. 3. Density of all concrete mixes.

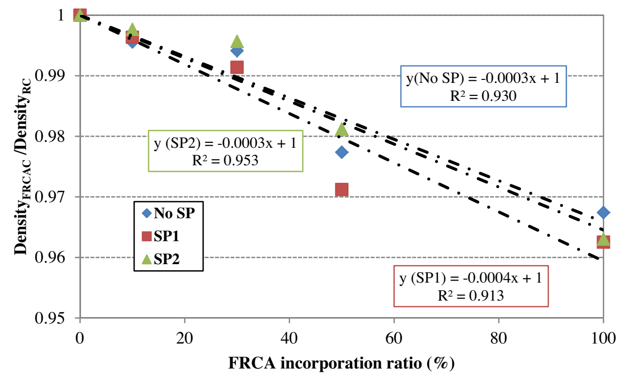

Fig. 4. Effect of FRCA incorporation on fresh density.

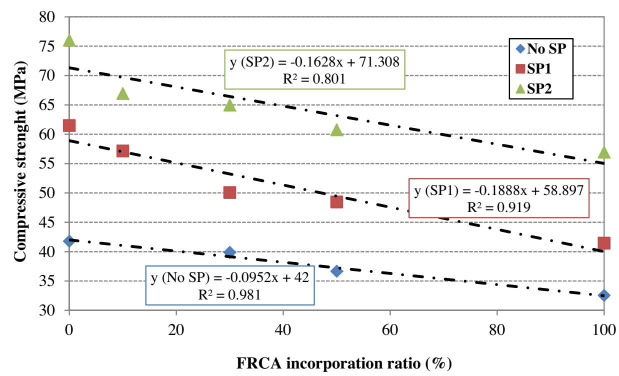

Fig. 5. Compressive strength at 7 days.

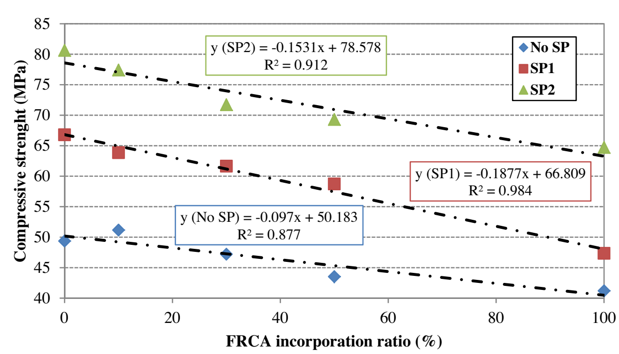

Fig. 6. Compressive strength at 28 days.

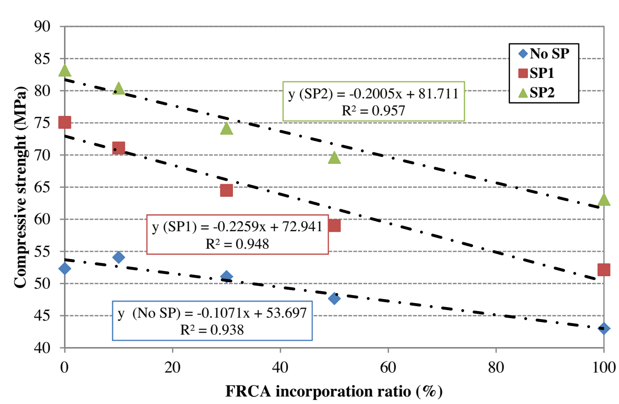

Fig. 7. Compressive strength at 56 days.

SP. According to standard NP EN 206-1:2007, the mixes of the C0 family were classified as C30/37, the mixes of the C1 family as C45/55, and the mixes of the C2 family as C60/75.

In all families the compressive strength decreases with the incorporation of FRCA, except for mix C0.10. Ledesma et al. [14] also obtained higher mechanical strength with low replacement ratios of FNA by FRCA. This was justified by the filler effect of the very fine broken particles from FRCA generated during the mixing process that offsets the higher porosity of the recycled aggregates. Replacement ratios higher than 10% had a negative effect on the mechanical performance of mixes. The lower compressive strength in mixes made with FRAC is justified by the lower friability coefficient of the recycled sand [39] and the higher $(w/c)_{ef}$ necessary to achieve the target slump. Using all results of the 15 mixes, a linear relationship between $(w/c)_{ef}$ and compressive strength was observed (Fig. 8).

Regarding the evolution of the compressive strength over time, Table 4 shows that at 7 days of age the mixes made without FRCA (C0.0; C1.0; C2.0) reached, respectively, 85%, 92% and 94% of the compressive strength at 28 days, which shows that the mixes made with SP harden faster.

The differences between the Ci.X families and its reference concrete Ci.0 decrease over time (Table 4). Therefore the ratio f_{cm7}/f_{cm28} and f_{cm28}/f_{cm56} decreases with the incorporation of FRCA. This is justified because the cement used in the manufacturing of the source concrete (CEM-II), from which the FRCA were obtained, contains fly ashes with longer setting time, compared to the cement used to produce the experimental campaign mixes (CEM-I), composed only of clinker. This phenomenon has been confirmed by other authors [23,29,32].

The effectiveness of the SP decreases with the incorporation of FRCA as shown in Fig. 9, where the slopes of the linear trend in the C1 and C2 concrete families were higher than in the C0 family. This is related to the loss of effectiveness of the SP in the reduction of $(w/c)_{ef}$. This phenomenon is more pronounced with the use of SP1. Similar results were obtained at 7 and 56 days of age.

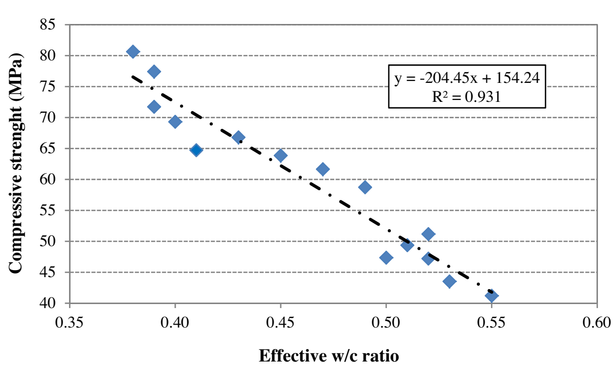

Fig. 8. Effective w/c ratio vs. compressive strength of concrete at 28 days.

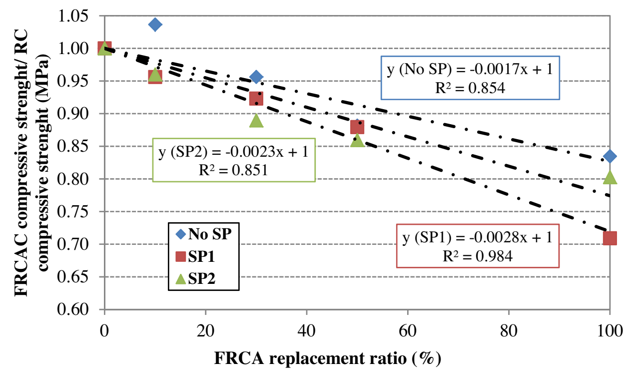

Fig. 9. Influence of FRCA and SP incorporation on the 28-day compressive strength.

Table 5 shows the percentage increase due to the use of SP1 and SP2 relative to the superplasticizer-free concrete (Δ_{SP}) for each level of replacement. The ratio $\Delta Ci.X/\Delta Ci.0$ is also calculated. Two trends can be observed from these results: (i) the loss of effectiveness of the SP with the use of FRCA; and (ii) the loss of effectiveness of the SP over time. SP1 incorporation resulted in a compressive strength improvement of 47.1% at 7 days of age, 35.3% at 28 days and 43.5% at 56 days (relative to C0.0), while SP2 incorporation resulted in an improvement of 81.9% at 7 days, 63.3% at 28 days and 59% at 56 days. Neville [51] (explains that the use of plasticizers leads to a greater dispersion of the cement particles and a more effective and rapid hydration, having an accelerating effect.

4.4. Shrinkage

Shrinkage tests were made according to LNEC specification E398:1993. The evolution of the shrinkage deformation for all the mixes tested is presented in Figs. 10–12. As expected shrinkage deformation increased over time following logarithmic curves with R^2 coefficients greater than 0.95. The highest values f shrinkage occur at early ages, where the loss of water by evaporation is more pronounced.

The incorporation of FRCA had a detrimental effect on concrete's shrinkage deformation. The FRCA's effect was influenced by the curing age. Tables 6 and 7 show the average of the shrinkage results for each mix at the age of 7 and 91 days, respectively. They also give the percentage of variation due to the use of FRCA for each concrete family (Δ_{FRCA}) and the percentage of variation due to the use of superplasticizers SP1 and SP2 with respect to the superplasticizer-free concrete (Δ_{SP}). At 91 days increases of 47%, 50% and 57% were observed for mixes C0.100, C1.100 and C2.100 respectively (relative to their reference mixes Ci.0). This can be explained by the lower stiffness of the FRCA and the greater $(w/c)_{ef}$ of the mixes with RA. At 7 days maximum increases of 28% and 11% were observed for mixes C0.100 and C1.50 respectively (a decrease of 14% was even observed for mix C2.30). This is

Table 4
Evolution of the relative compressive strength.

Replacement ratio (%)	C0				C1				C2			
	$f_{cm\ 7}/f_{cm\ 28}$ (%)	$\Delta_{C0.X/C0.0}$ (%)	$f_{cm\ 56}/f_{cm\ 28}$ (%)	$\Delta_{C0.X/C0.0}$ (%)	$f_{cm\ 7}/f_{cm\ 28}$ (%)	$\Delta_{C1.X/C1.0}$ (%)	$f_{cm\ 56}/f_{cm\ 28}$ (%)	$\Delta_{C1.X/C1.0}$ (%)	$f_{cm\ 7}/f_{cm\ 28}$ (%)	$\Delta_{C2.X/C2.0}$ (%)	$f_{cm\ 56}/f_{cm\ 28}$ (%)	$\Delta_{C2.X/C2.0}$ (%)
0	84.63	0.00	105.98	0.00	92.04	0.00	112.39	0.00	94.27	0.00	103.18	0.00
10	–	–	105.67	−0.30	89.50	−2.84	111.32	−0.96	86.46	−8.29	103.86	0.65
30	84.46	−0.20	108.20	2.09	81.20	−13.35	104.61	−7.44	90.55	−3.94	103.38	0.19
50	84.24	−0.46	109.49	3.31	82.52	−11.54	100.47	−11.87	87.66	−7.01	100.44	−2.72
100	79.00	−6.65	104.37	−1.52	87.52	−5.17	110.09	−2.09	88.00	−6.65	97.48	−5.85

Table 5
Increase in compressive strength due to the use of SP at different ages and replacement ratios.

Replacement ratio (%)	7 days				28 days				56 days			
	Δ_{SP1} (%)	$\Delta_{C1.x}/\Delta_{C1.0}$ (%)	Δ_{SP2} (%)	$\Delta_{C2.x}/\Delta_{C2.0}$ (%)	Δ_{SP1} (%)	$\Delta_{C1.x}/\Delta_{C1.0}$ (%)	Δ_{SP2} (%)	$\Delta_{C2.x}/\Delta_{C2.0}$ (%)	Δ_{SP1} (%)	$\Delta_{C1.x}/\Delta_{C1.0}$ (%)	Δ_{SP2} (%)	$\Delta_{C2.x}/\Delta_{C2.0}$ (%)
0	47.15	1.00	81.95	1.00	35.29	1.00	63.33	1.00	43.47	1.00	59.01	1.00
10	–	–	–	–	24.80	0.70	51.29	0.81	31.47	0.72	48.69	0.83
30	25.56	0.54	62.91	0.77	30.60	0.87	51.95	0.82	26.26	0.60	45.18	0.77
50	32.18	0.68	65.70	0.80	34.94	0.99	59.23	0.94	23.81	0.55	46.07	0.78
100	27.31	0.58	74.96	0.91	14.93	0.42	57.07	0.90	21.23	0.49	46.70	0.79

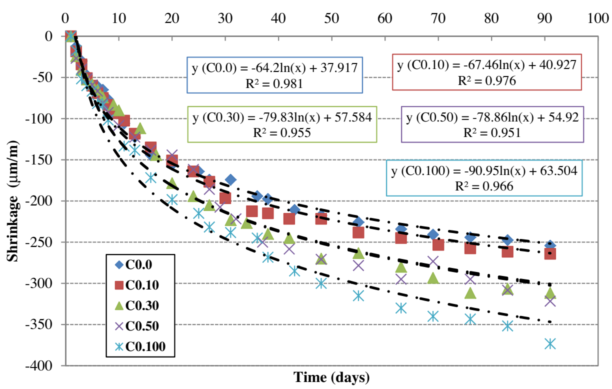

Fig. 10. Shrinkage deformation over time for the C0 family.

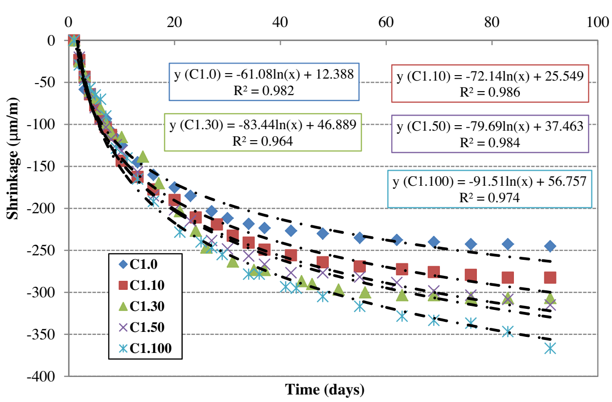

Fig. 11. Shrinkage deformation over time for the C1 family.

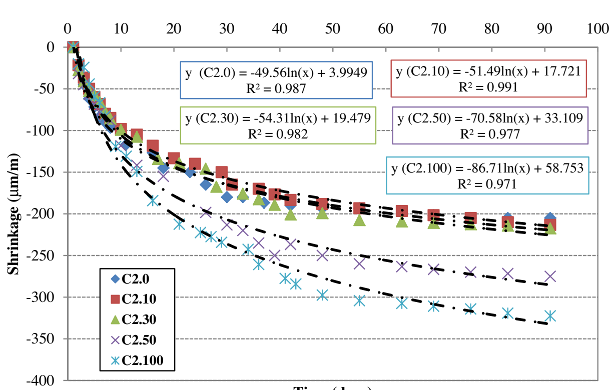

Fig. 12. Shrinkage deformation over time for the C2 family.

Table 6
Shrinkage deformation at 7 days for each of the concrete families and FRCA replacement ratios.

Replacement ratio (%)	No SP		SP1		SP2	
	Δ_{FRCA} (%)	Δ_{SP} (%)	Δ_{FRCA} (%)	Δ_{SP} (%)	Δ_{FRCA} (%)	Δ_{SP} (%)
0	0.00	0.00	0.00	43.59	0.00	38.46
10	15.38	0.00	10.71	37.78	−11.11	6.67
30	14.10	0.00	5.36	32.58	−13.89	4.49
50	24.36	0.00	10.71	27.84	−7.41	3.09
100	28.21	0.00	−3.57	8.00	−8.33	−1.00

Table 7
Shrinkage deformation at 91 days of each of the concrete families and FRCA replacement ratios.

Replacement ratio (%)	No SP		SP1		SP2	
	Δ_{FRCA} (%)	Δ_{SP} (%)	Δ_{FRCA} (%)	Δ_{SP} (%)	Δ_{FRCA} (%)	Δ_{SP} (%)
0	0.00	0.00	0.00	−3.61	0.00	−19.34
10	3.93	0.00	15.31	6.94	4.07	−19.24
30	22.62	0.00	25.17	−1.60	6.10	−30.21
50	26.56	0.00	28.57	−2.07	34.15	−14.51
100	46.89	0.00	49.66	−1.79	57.32	−13.62

justified because at early ages the evaporated water of the specimens is partly offset by the water absorbed by the FRCA during the mixing process. Hence the dimensional changes at 7 days are smaller than those produced at the age of 91 days where less water is available in the FRCA's pores.

At early ages the use of SP increased the shrinkage deformation with respect to the C0 family (Table 6). This was attributed to the altered distribution of the particles caused by the SP, which promotes evaporation of water at early ages and the corresponding faster volume change of the specimens. In conventional concrete, Zhang et al. [52] also showed that the addition of SP increased the early drying shrinkage. On the other hands, at 91 days the use of SP1 and SP2 reduced the shrinkage by 3.6% and 19.3% relative to the FRCA-free mixes. This reduction is lower in the mixes with 100% FRCA: 1.8% and 13.6% with SP1 and SP2 respectively. The results demonstrate that SP2 has a higher ability to improve the shrinkage than SP1.

Fig. 13 shows the influence of SP and FRCA on the shrinkage at 91 days. The three concrete families showed similar behaviours, although lower shrinkage values were observed in the SP2 family, coinciding with the mixes with lower $(w/c)_{ef}$. Since the use of the SP significantly reduced $(w/c)_{ef}$, better results of the shrinkage deformation were expected. However, considering the results of the 15 mixes, no clear relationship between the $(w/c)_{ef}$ and shrinkage deformation was observed (Fig. 14).

Regarding the effect of the FRCA, the results are very consistent with those by other authors [30–32,39] and contrasted with those of Manzi et al [41]. Regarding the effect of SP, the results agree with those obtained by Merlet and Pimienta [34] The results

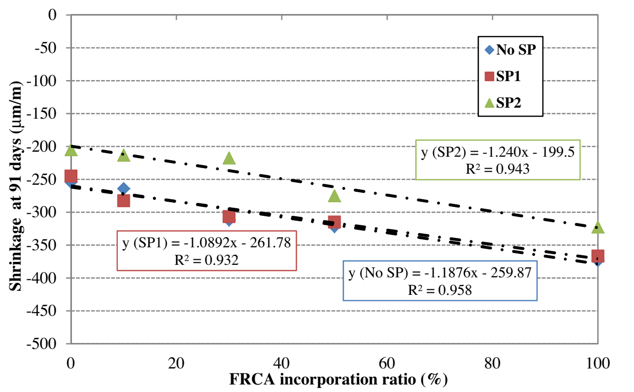

Fig. 13. Influence of SP and FRCA replacement ratio on the shrinkage at 91 days.

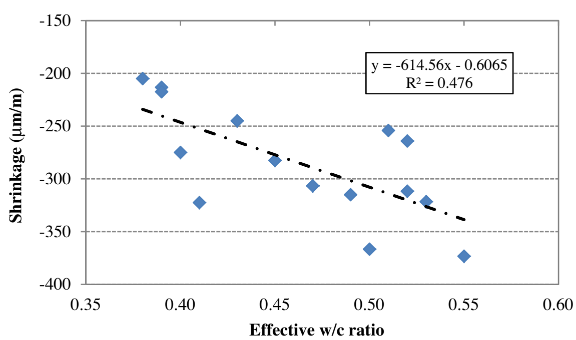

Fig. 14. Effective w/c ratio vs. shrinkage at 91 days.

obtained by these authors have been commented in detail in the literature review section.

To test the quality of the results, the shrinkage value for each mix was calculated following the expressions proposed by Eurocode-2. The results were compared with those obtained experimentally in this work (Fig. 15). As seen for the three families the calculated shrinkage values were higher than those obtained experimentally. These results are coherent since Eurocode-2 is a document prepared to design structures and the suggested shrinkage values are upper bounds with respect to those obtained experimentally.

4.5. Creep

Creep tests were made according to LNEC specification E399:1993. Fig. 16 shows the evolution of creep deformation for all mixes tested. The curves that best represent the creep deformation over time are logarithmic, since most of the deformation occurs in the early ages, and then they tend to stabilize.

The reference concrete (C0.0) showed the lowest mean values of the creep deformation at any age. The incorporation of FRCA increased the creep deformation in the three concrete families. At 28 days increases of 129%, 122% and 49% (relative to C0.0) were observed for mixes C0.100, C1.100 and C2.100 respectively. The incorporation of SP1 did not improve the creep deformation of mix C1.100 relative to the superplasticizer-free mix (C0.100). This can be explained by the higher specific surface of the FRCA that harms the action of the regular superplasticizer based on lignosulfonate with addition [34]. The incorporation of SP2 improved the creep deformation of mix C2.100 with respect to the mix C0.100 at 28 days. Zhang et al. [53] demonstrated that the use of polycarboxylic superplasticizers significantly reduced the creep

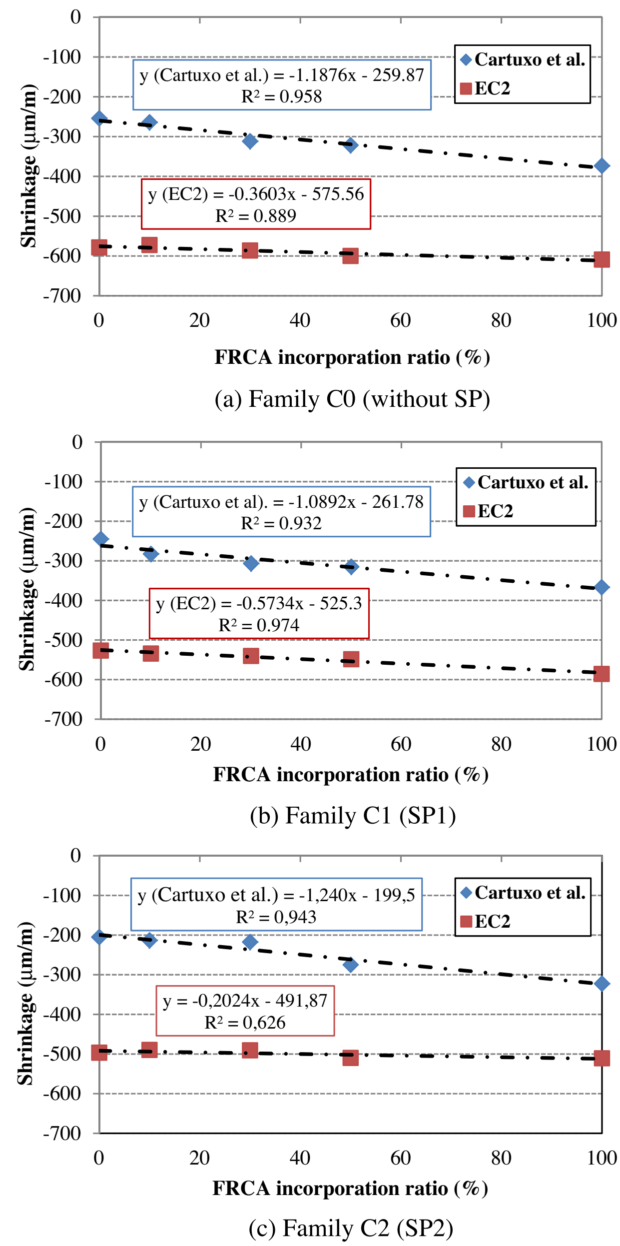

Fig. 15. Experimental shrinkage vs. prediction values from EC-2.

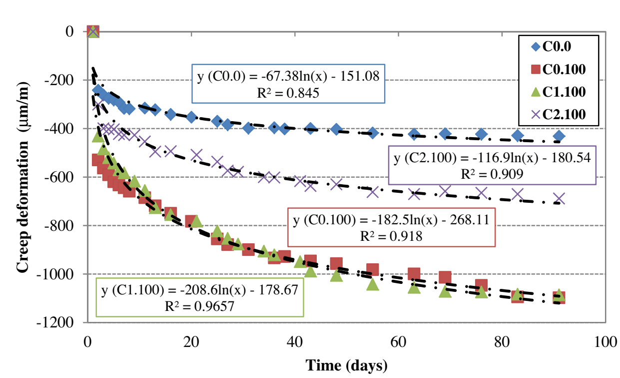

Fig. 16. Evolution of creep deformation.

of conventional concrete. These authors concluded that polycarboxylic superplasticizers decrease the internal moisture transmission and diffusion to external environment, improving the

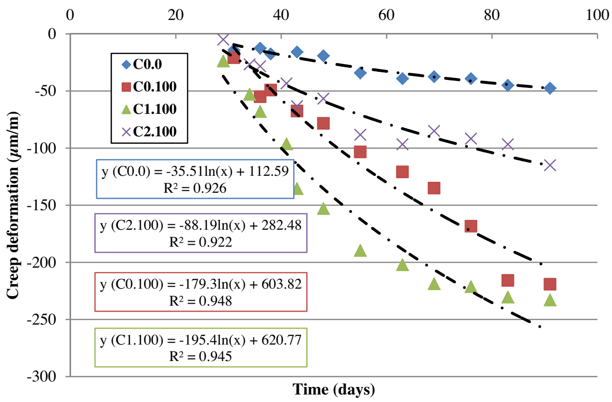

Fig. 17. Evolution of creep deformation after 28 days of loading (starting 1 day after casting).

hydration of cement and consequently increasing strength and decreasing creep.

After 28 days of curing the behaviour of the four mixes tested was different as seen in Fig. 17. All mixes tend to follow a logarithmic curve. The reference mix (C0.0) tends to stabilize its creep deformation faster than mixes made with FRCA. At 92 days of loading, the reference mix C0.0 showed a creep deformation 10.2% higher than that shown at 28 days, while the mix C0.100 showed an increase of 24%. The use of SP1 did not improve concrete's behaviour with respect to this property, since mix C1.100 showed an increase of 26%, a value very similar to that shown by the superplasticizer-free mix. The mix made with SP2 (C2.100) showed an increase of 20%, which represented an improvement over the other mixes made with FRCA, but was twice that of the reference mix made with FNA. At 91 days increases of 154%, 152% and 60% were observed (relative to C0.0) for mixes C0.100, C1.100 and C2.100 respectively, suggesting that as time passes the gap between the reference mix and the mixes made with FRCA increases.

No relationship between the creep deformation and $(w/c)_{ef}$ was observed. Also, no relationship was observed with the modulus of elasticity of the mixes (Table 8). Therefore, the physico-mechanical properties of the aggregates are the most important parameter in this property. The negative effects of the incorporation of FRCA exceed the beneficial effects of the superplasticizers to reduce $(w/c)_{ef}$ and to improve the modulus of elasticity of concrete. These results should be taken into account to decide when to load the concrete structure and/or to decide when to remove the formwork/shoring.

Table 8
28-Day modulus of elasticity.

	E_c 28 days (MPa)
C0.0	37,000
C0.100	32,100
C1.100	36,800
C2.100	42,700

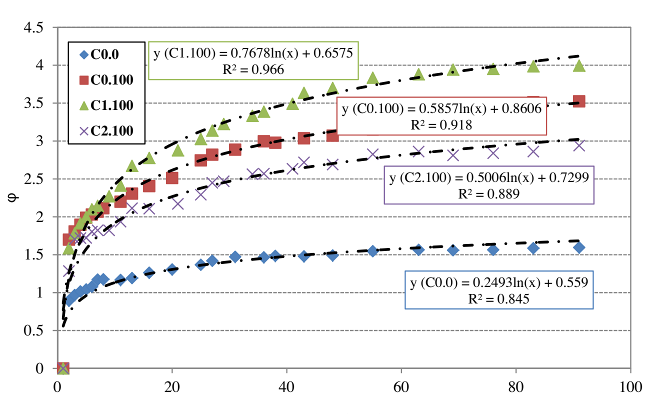

Fig. 18. Creep coefficient over time.

Table 9
Specific creep deformation (µm/m·MPa).

Authors	Specific creep deformation at 28 days (µm/m·MPa)			Specific creep deformation at 91 days (µm/m·MPa)		
	0% FRCA	100% FRCA	Δ_{FRCA} (%)	0% FRCA	100% FRCA	Δ_{FRCA} (%)
Cartuxo et al.	38	88	130	43	110	156
Domingo-Cabo et al. (2011)	16	23	44	24	33	38
Fathifazl et al. (2011)	60	75	25	71	125	76
Manzi et al. (2013)	–	–		70	99	41

Fig. 18 shows the creep coefficient and its logarithmic evolution over time. Domingo Cabo et al. [49] obtained a creep coefficient of 0.6 at 28 days, lower than that obtained in this study for mix C0.0. Fathifazl et al. [38] measured values around 1.5, which is consistent with our measurements. To compare with other authors, the specific creep was calculated (Table 9). As expected the creep coefficients given in this study are higher than those of other authors, as tests begin at one day, while in most literature references tests begin at 28 days.

5. Conclusions

This paper demonstrated that to use FRCA for concrete production it is necessary to take into account the different rheological behaviour. The following conclusions can be draw:

1. The incorporation of FRCA up to 100% had the following consequences on the concrete's rheological properties:
   - For the same slump value, the $(w/c)_{ef}$ increased up to 16.3%.
   - The fresh bulk density decreased up to 3.7%.
   - The compressive strength decreased up to 35% at 7 days, 29% at 28 days and 30% at 56 days.
   - The shrinkage deformation increased up to 28% at 7 days and 57% at 91 days.
   - The creep deformation increased up to 129% at 2 days and 154% at 91 days.
2. The addition of a regular superplasticizer in concrete with FRCA had the following consequences on the concrete's rheological properties:
   - For the same slump value, the $(w/c)_{ef}$ decreased up to 15.7%.
   - The fresh bulk density increased up to 2.3%.
   - The compressive strength increased up to 47% at 7 days, 35% at 28 days and 43% at 56 days.
   - The shrinkage deformation increased up to 44% at 7 days of age and decreased up to 2% at 91 days.
   - The creep deformation decreased up to 2.2% at 28 days of age and 1.1% at 92 days (relative to the superplasticizer-free family).
3. The addition of a high-performance superplasticizer in concrete with FRCA had the following consequences on the concrete's rheological properties:
   - For the same slump value, the $(w/c)_{ef}$ decreased up to 25.5%.
   - The fresh bulk density increased up to 2.3%.

- The compressive strength increased up to 82% at 7 days, 63% at 28 days and 59% at 56 days.
- The shrinkage deformation increased up to 38% at 7 days and decreased up to 30% at 91 days.
- The creep deformation decreased up to 35% at 28 days and 37% at 92 days (relative to the superplasticizer-free family).

By comparison with parallel studies concerning the mechanical and durability properties of concrete with FRCA, it can be stated that the rheological properties are the ones in which the incorporation of FRCA has the most deleterious effects. However, that is not a deterrent to using this type of recycled aggregates, since the addition of high-performance superplasticizers more than offsets the negative effects of FRCA. Nevertheless, this is a subject that must be carefully scrutinised at the design stage whenever the environmentally positive measure is being considered.

6. Standards used in the experimental work

LNEC E397:1993. Concrete. Determination of the modulus of elasticity in compression (in Portuguese). LNEC, Portugal.

LNEC E398:1993. Concrete. Determination of shrinkage and expansion (in Portuguese). LNEC, Portugal.

LNEC E399:1993. Concrete. Determination of creep in compression (in Portuguese). LNEC, Portugal.

NP EN 206-1:2007. Concrete. Part 1: Specification, performance, production and conformity (in Portuguese), IPQ, Portugal.

NP EN 934-2:2009. Admixtures for concrete, mortar and grout – Part 2: Concrete admixtures – Definitions, requirements, conformity, marking and labelling (in Portuguese), IPQ, Portugal.

NP EN 12350-2:2009. Testing fresh concrete. Slump test (in Portuguese), IPQ, Portugal.

NP EN 12350-6:2009. Testing fresh concrete. Density (in Portuguese), IPQ, Portugal.

NP EN 12390-3:2009. Testing hardened concrete - Part 3: Compressive strength of test specimens (in Portuguese). IPQ, Portugal.

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