Concrete made with fine recycled concrete aggregates

The effect of superplasticizers on workability and compressive strength

The use of recycled concrete aggregates to produce new structural concrete is a relevant solution towards the development of a more sustainable society. It is accepted as a good alternative to dumping obsolete concrete leftovers and it helps to preserve the natural aggregates' reserves. This research sets out to limit the disadvantages associated with the performance of concrete with several replacement ratios of fine natural aggregates (FNA) by fine recycled concrete aggregates (FRA) by using two superplasticizers, which differ mainly in the water reduction capacity and robustness. The workability, density and compressive strength of each of the mixeswas analysed and then compared.

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The characteristics of recycled aggregates (RA), the concrete composition and the type of superplasticizer have great influence on the mechanical performance of recycled aggregates concrete. Even though there are various studies on the influence of the two first parameters very little is known about the interaction between superplasticizers and RA. Therefore this paper aims to analyse the influence of FRA on the mechanical performance of concrete as well as the effect of superplasticizers on the properties of this modified concrete. Superplasticizers have various effects on concrete, such as increasing its rupture stress, allowing lower cement content while maintaining strength and workability, increasing workability with the same water and cement contents, and decreasing per-meability [1].

The experimental programme started with the production of the recycled aggregates from a concrete produced in the laboratory. Thus the production and the main characteristics of the component materials could be adequately controlled.

Concrete mixes without superplasticizers, as well as mixes with a regular and a high performance superplasticizer were produced and five mixes with different FRA incorporation ratios were then made for each of these concrete types. In order to establish a comparative basis the various mixes were tested in fresh state for their slump and density. The slumpwas kept constant for all concrete mixes studied (levelling parameter).

After curing, the concrete mixes were tested in the hardened state for compressive strength and stress-strain diagrams were drawn. The experimental results were then analysed and correlations were established between the properties of fine recycled concrete aggregates concrete (FRC), the properties of FRA, the replacement ratios of FNA by FRA and the superplasticizer used.

Experimental programme

Original concrete

The Original Concrete (OC) was produced in a ready-mixed concrete plant and poured into moulds in the laboratory, with ambient curing conditions. Its composition is typical of a commercial concrete, designed to correspond to a C 30/37, X0 (P), S3, Cl 0.40, D_{max} 25 mm according to NP EN 206-1. The composition of the OC is provided in Table 1. The slump and 28-day average compressive strength (in 150 mm cubes) were 120 mm and 37.3 MPa, respectively.

FRA production and aggregates characterization

After a 28 day curing period the OC blocks were crushed using a jaw-crusher. Properties such as the fines percentage and maximum aggregate size (smallest sieve through which at least 90% of the aggregate's mass could pass), which are relevant in the production of FNA, were regulated through the closed size setting of the crusher. In order to allow an exact replacement of the natural aggregates, the percentage of FRA material passing through each sieve must be exactly the same as the combination of fine and coarse sands.

Four types of natural aggregate (NA) were used (two fine siliceous sands and two coarse calcareous stones), plus the FRA. The FRA and the NA were characterised and the main results are presented in Table 2. FRA particle densities and loose bulk density are lower than those of FNA because of their greater porosity, which is linked to the adhering mortar. The water absorption of FRA (10.9%) is clearly above that found for FNA.

Superplasticizers used

The regular superplasticizer, henceforth called SP1, is based on lignosulfonate with additions, and the high performance one, henceforth called SP2, is based on a combination of modified polycarboxylates in an aqueous solution. Besides the superplasticizer-free reference concrete (RC0), two other reference concrete mixes were produced, without FRA and with the addition of the superplasticizers (RC1 and RC2). The superplasticizer content of RC1 and RC2 was 1% of cement mass and, in order to keep slump within the specified range of

Table 1: Composition of original concrete

	Quantity (kg/m^3)
Cement II/A-L 42.5R	224
Fly ash	121
Water	165
Fine natural sand (FNA1)	216
Coarse natural sand (CNA1)	437
Limestone fine natural gravel (FNA1)	215
Limestone medium natural gravel	326
Limestone coarse natural gravel (CNA2)	633
Superplasticizer	3.45

120 ± 10 mm, the water/cement ratio was decreased to offset the water reduction effect of the superplasticizers.

Concrete mixes' composition

Based on the Faury concrete design [2] five concrete mixes were produced for each superplasticizerand for the concrete without superplasticizers: a reference concrete (RC) and four RCs with FNA/RA replacement ratios of 10%, 30%, 50% and 100%. Every mix has the same effective aggregates size distribution and cement content. The lower water content implied higher aggregates content so that the cement and superplasticizer content and the proportion of the aggregate fractions could be kept constant. Table 3 summarises the composition of the mixes.

Concrete mixes with FRA

The recycled concrete aggregates have a significant water absorption capacity in a concrete mix. The simple volume replacement of NA by RA affects concrete workability and performance. For the mixing period of 10 minutes [3], it was found that the FRA had absorbed 50% of its potential capacity. Therefore, to compensate for the FRA's water absorption during mixing, extra water was added to the mix.

This amount is obtained by calculating the difference between the maximum quantity taken in 10 minutes and that already within the FRA before mixing (it is not oven-dried). The water/cement ratios of the various mixes were also corrected to obtain the target slump, bearing in mind the increased internal friction of the mixes with FRA.

Tests on concrete mixes

Fresh concrete was tested for workability and specific density according to NP EN 12350-2 and NP EN 12350-6, respectively. Seven, 28 and 56-day compressive strength was evaluated in 150 mm cubes, in accordance with NP EN 12390-3, considering 3, 5 and 3 specimens for each age, respectively.

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Results and discussion

Workability

Figure 1 presents the results of the Abrams cone slump test for all FNA/FRA replacement ratios. It shows that all mixes met the target workability apart from C0,100 (concrete without superplasticizer and 100% replacement of FNA by FRA). The lower slump achieved for this particular case means that the optimal water/cement ratio should be slightly higher than that used.

Figure 2 shows the relationship of the effective water/cement ratios between concrete mixes with superplasticizers and those without. It also shows the water reduction capacity of the superplasticizers as a function of the replacement ratio of NFA by RCFA. There isa linear relationship between the reduction of the effectiveness of the superplasticizers and the RCFA incorporation ratio, with excellent correlations. The results indicate that SP1 is slightly more sensitive to the presence of RCFA than SP2 (easily seen in the slopes of the lines - the slope for SP1 is over 50% higher than that for SP2). As the lignosulfonatebased superplasticizers (SP1) act mainly by electrostatic repulsion and partially by steric hindrance, adsorbing onto the surface of the cement particles,

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
AFRB (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
CNA 1 (kg)	275	275	275	275	275	288	288	286	285	282	298	296	296	295	293
CNA 2 (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

Table 5: Compressive strength

			7 days			28 days			56 days		
			WS	SP1	SP2	WS	SP1	SP2	WS	SP1	SP2
RC	f_{cm}	(MPa)	30.4	43.9	52.6	39.5	53.3	65.2	42.7	58.8	68.3
	Δ_{FRA}	(%)	-	-	-	-	-	-	-	-	-
	Δ_{SP}	(%)	-	44.4	73.0	-	34.9	65.1	-	37.7	60.0
C*.10	f_{cm}	(MPa)	32.8	45.3	53.6	40	53.7	64.6	42.8	59.4	68.5
	Δ_{FRA}	(%)	7.9	3.2	1.9	1.3	0.8	-0.9	0.2	1.0	0.3
	Δ_{SP}	(%)	-	38.1	63.4	-	34.3	61.5	-	38.8	60.0
C*.30	f_{cm}	(MPa)	30.8	42.8	54.5	38.6	51	65.4	41.7	53.4	67.2
	Δ_{FRA}	(%)	1.3	-2.5	3.6	-2.3	-4.3	0.3	-2.3	-9.2	-1.6
	Δ_{SP}	(%)	-	39.0	76.9	-	32.1	69.4	-	28.1	61.2
C*.50	f_{cm}	(MPa)	29.7	40.1	52.7	37.6	47.8	63.2	41.8	53.4	64.9
	Δ_{FRA}	(%)	-2.3	-8.7	0.2	-4.8	-10.3	-3.1	-2.1	-9.2	-5.0
	Δ_{SP}	(%)	-	35.0	77.4	-	27.1	68.1	-	27.8	55.3
C*.100	f_{cm}	(MPa)	29.5	37.5	51.4	38.6	45.1	63	40.2	47.4	62.6
	Δ_{FRA}	(%)	-3.0	-14.6	-2.3	-2.3	-15.4	-3.4	-5.9	-19.4	-8.3
	Δ_{SP}	(%)	-	27.1	74.2	-	16.8	63.2	-	17.9	55.7

the reduction of their performance is probably because they interact with more cement particles, as a consequence of the replacement of NFA by RCFA, for the same content of superplasticizer. SP2 is made with polycarboxylic acids and so the dispersion phenomenon is mainly due to a steric hindrance effect [4, 5] which increases the zeta potential of cement particles [6], and thus the presence of RCFA seems to have less effect on SP2's performance than it does on SP1's.

Specific density of concrete

The results (Table 4) presented in relative terms in Figure 3, show that the incorporation of FRA, which has lower particle density than FNA, leads to a decrease in the concrete's density. These results obtained high correlation factors (R2 above 0.95) considering non-linear relationships. Since the regression line of the SP2 family had the smaller slope, followed very closely by the superplasticizer-free family and then by the SP1 family, it indicates that when SP2 was used the greater compacity of concrete somehow offset the relative increase in water/cement ratio due to the incorporation of FRA.

Table 4: Specific density

	Density (kg/m^3)				
	0%	10%	30%	50%	100%
WS	2,395	2,378	2,363	2,349	2,309
SP1	2,452	2,430	2,406	2,390	2,370
SP2	2,476	2,454	2,446	2,430	2,418

Compressive strength

The average compressive strength (fcm) measured at 7, 28 and 56 days for all FCRA incorporation ratios and superplasticizers are presented in Table 5. It also gives the variations found as a function of the FCRA incorporation ratio (ΔFRA), for each superplasticizer family, and as a function of the superplasticizer type (ΔSP), for each FCRA incorporation ratio. Figures 4 to 6 show the variations in compressive strength with the FCRA incorporation ratio.

After 28 days curing all FRCs showed a decrease in compressive strength due to the incorporation of FRA, with figures of 4.8%, 15.4% and 3.3% for the WS, SP1 and SP2 families, respectively. These reductions are insignificant for the superplasticizer-free and SP2 concrete mixes and it can even be said that the compressive strength remains approximately constant. The addition of superplasticizers in the mixes led to compressive strength gains of up to 34.8% and 69.5% for the SP1 and SP2 families respectively. These strength gains increase with the water reducing capacity of the superplasticizer, due to a reduction in the

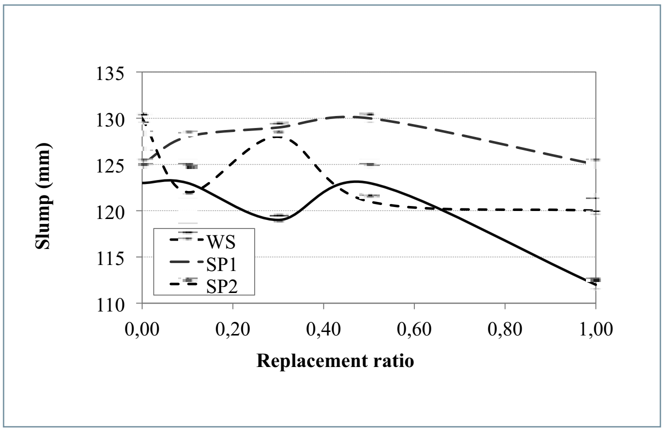


Fig. 1: Slump versus effective water/cement ratio for all FNA/CRFA replacement ratios

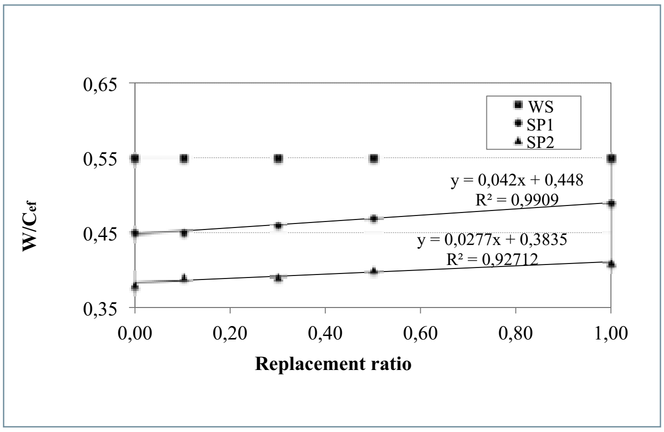


Fig. 2: Superplasticizer water reduction capacity versus FNA/CRFA replacement ratio

water/cement ratio. But with higher replacement ratios, the effect of the lower mechanical characteristics of FRA gains more importance. FRC made with SP1 show a more drastic reduction in compressive

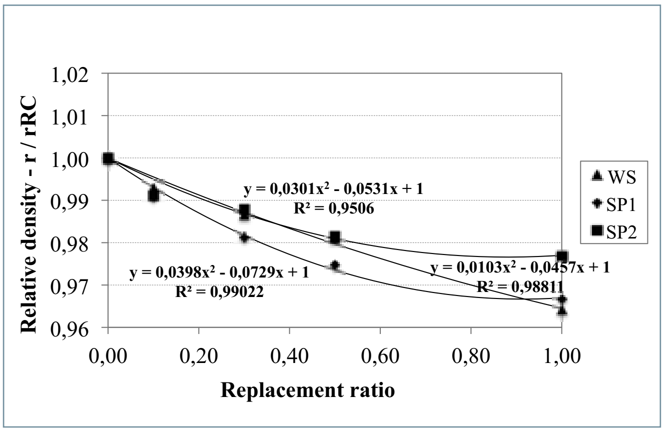


Fig. 3: Relative density of FRC versus superplasticizers used

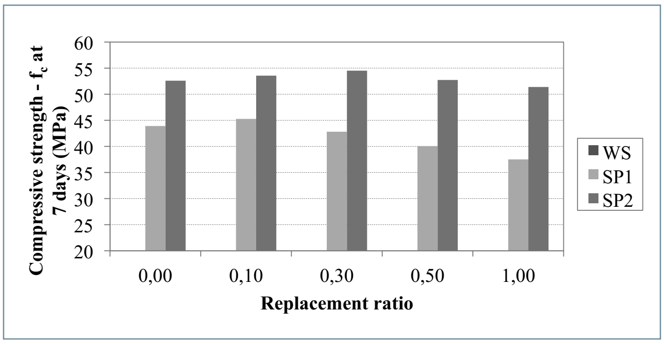


Fig. 4: Compressive strength versus FNA/FRA replacement ratio at 7 days

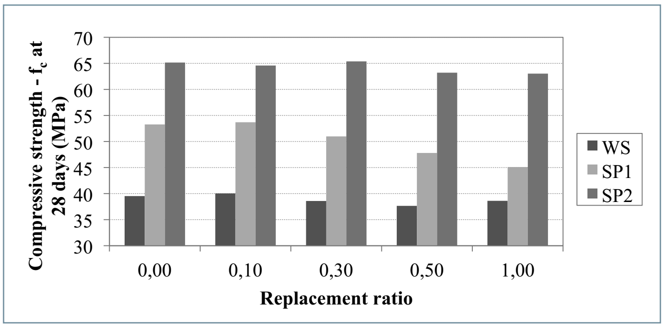


Fig. 5: Compressive strength versus FNA/FRA replacement ratio at 28 days

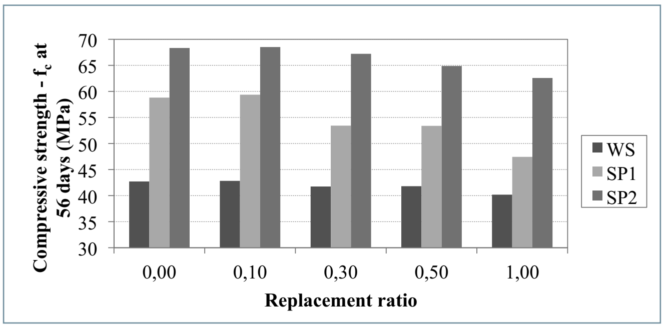
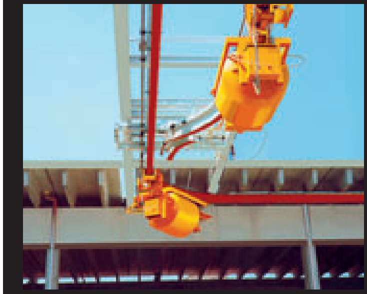


Fig. 6: Compressive strength versus FNA/FRA replacement ratio at 56 days



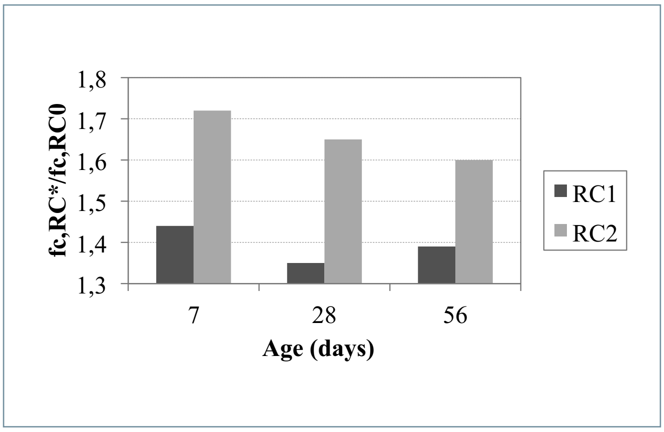


Fig. 7: Evolution of the relative compressive strength of the reference concrete mixes

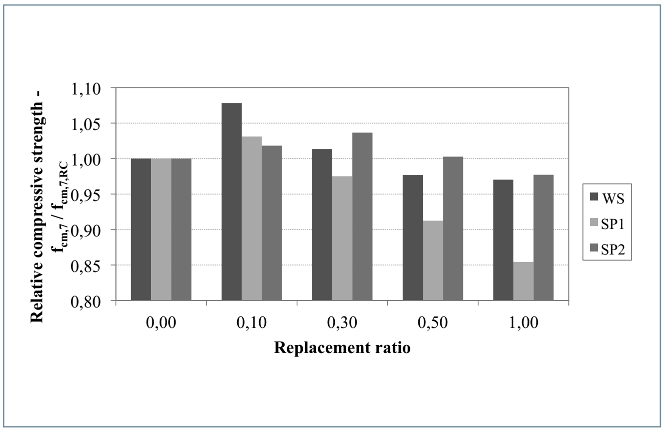


Fig. 8: FRC relative 7-day compressive strength

strength with increased incorporation of FRA than the other mixes, since the increase in the effective w/c ratio was also bigger. Figure 7 indicates that the influence of the superplasticizers increases with shorter curing times. This is related to the dispersant capacity of the superplasticizers that were used, which allow a much quicker cement hydration that rises with theirrelative efficiency. The general trend of the lines in Figures 8 to 10, for 7, 28 and 56 days of curing, indicates that concrete's sensitivity to the presence of FRA increases with age.

In fact, the relative strength losses grow for every mix with FRA as the test specimens age, compared with the concrete without these aggregates. It seems that the favourable effects of the superplasticizers tend to fade as the concrete matures.

The determination of stress/strain constitutive laws of the concrete mixes studied did not reveal behavioural differences caused by the incorporation of FRA. However, the use of superplasticizers did lead to an increase in yielding stress and a reduction of the yielding path length, typical characteristics of a high-performance concrete. Figures 11 to 13 show the stress/strain constitutive laws of the concrete mixes tested,

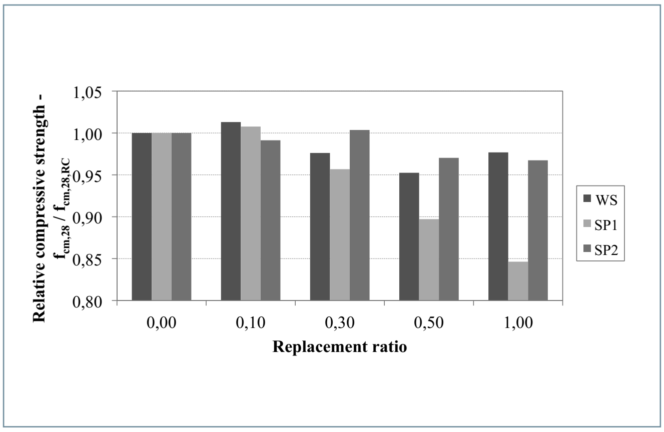


Fig. 9: FRC relative 28-day compressive strength

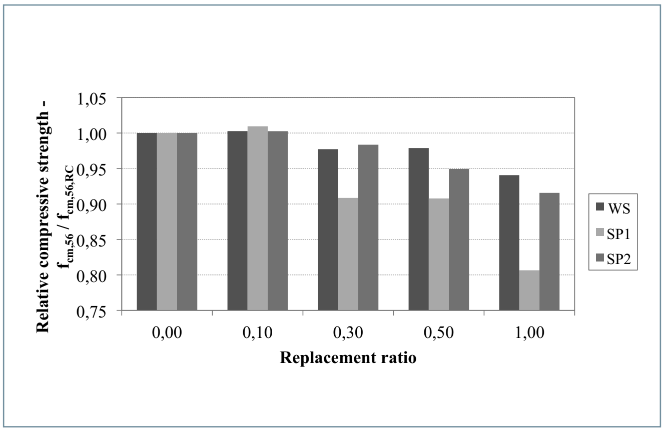


Fig. 10: FRC relative 56-day compressive strength

grouped by content and type of superplasticizer. For RC0 the yielding path is particularly conspicuous. However, for RC1 this path almost vanished as the maximum stress increased, and for RC2 these trends are even more marked, leading to a rupture that may be considered as fragile. The phenomenon of ductility loss as the compressive strength increases is well known [7] and is associated with the brisker propagation of cracking as the compressive strength goes up. The evolution of stress with strain shows that there is an earlier loss of stiffness in mixes with FRA. This is because the AFR paste is more fragile, which facilitates cracking propagation [8] and is directly linked with the lower compressive strength.

Figure 14 shows the gains of the RC and FRC made with superplasticizers over the superplasticizer-free mixes that have the same FNA/FRA replacement ratio. The 28-day compressive strength gains attributable to the superplasticizers were higher for RC than for FRC, though the difference is slight.

This can be justified by the increase in specific surface of FRA in the mix for the same superplasticizers content, given the fact that RA are longer and more angular than NA.

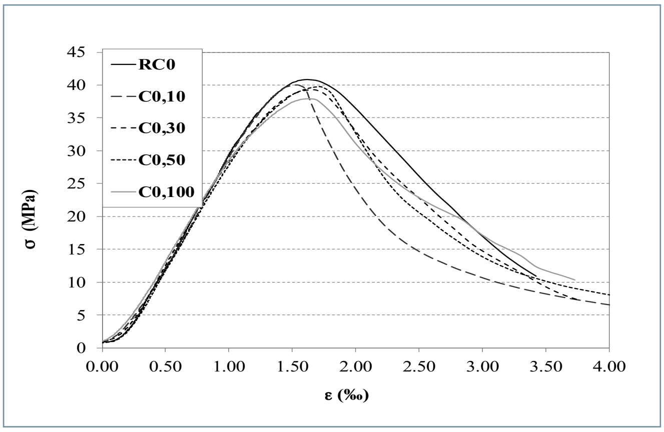


Fig. 11: Stress (σ)/strain (ε) constitutive laws of the RC0and C0 concrete mixes (without superplasticizers).

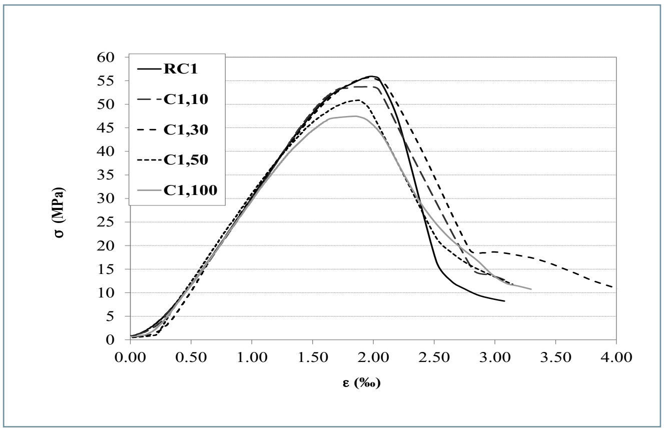


Fig. 12: Stress (σ)/strain (ε) constitutive laws of the RC1 and C1 concrete mixes (with superplasticizer SP1)

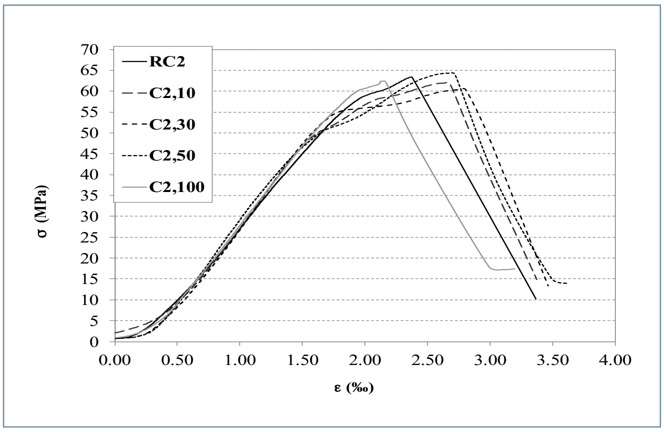


Fig. 13: Stress (σ)/strain (ε) constitutive laws of the RC2 and C2 concrete mixes (with superplasticizers SP2)

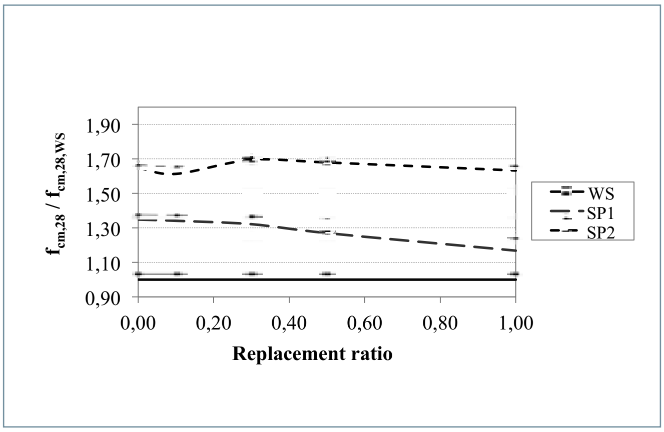


Fig. 14: Influence of the superplasticizers on the compressive strength of RC and FRC

Conclusions

The following conclusions can be drawn from the experimental results:

1. Concerning the workability, the efficiency of superplasticizers decreases with the increase of the FRA incorporation ratio
2. The greater compacity of the mix provided by the superplasticizers may prevail over the effect of the higher water/cement ratio in the determination of the specific density of FRC
3. FRC showed compressive strength gains, which were greater with increasing water re-duction capacity of the superplasticizer
4. The strength increase from using superplasticizers is clearly associated with the reduction of the water/cement ratio
5. The high-performance superplasticizer showed to be more robust in the presence of FRA, when compared with the regular superplasticizer which suffered bigger relative compressive strength losses
6. The effect of superplasticizers on compressive strength is more pronounced with lower FRA incorporation in the mix
7. The σ−ε curves suggest that concrete made with FRA has a similar behaviour to con-ventional concrete of the same compressive strength

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