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Effect of supplementary cementitious materials on the fresh and hardened performance of self-compacting concrete incorporating different aggregate types

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Abstract:
This study examines the combined effect of aggregate type and blended binder composition on the fresh and hardened performance of self-compacting concrete (SCC). Fourteen mixtures were produced in two parallel series under identical mix-design conditions: one with natural coarse aggregates (NCA) and one with recycled coarse aggregates (RCA). Cement was partially replaced with silica fume (SF), ground granulated blast-furnace slag (GGBFS), and natural pozzolan (NP). All mixtures satisfied the European Guidelines (EFNARC) requirements, with slump-flow values of 600–750 mm, T_{500} times of 2.00–2.95 s, V-funnel times of 5.11–9.75 s, L-box ratios of 0.83–0.95, and segregation ratios of 6.4–11.4%. Among the blended mixtures, the quaternary binder containing 5% SF, 15% GGBFS, and 5% NP showed the best overall balance, reaching 54.1 MPa with NCA and 48.9 MPa with RCA at 120 days while reducing 28-day sorptivity. At 28 days, UPV results indicated generally good internal quality. The main contribution of this work is to demonstrate that, under constant formulation constraints, an optimised multi-SCM binder can reduce the performance gap between NCA- and RCA-based SCC and support the development of more sustainable SCC with lower cement content.

Keywords:
self-compacting concrete, recycled concrete aggregates, supplementary cementitious materials, workability, mechanical properties

1. Introduction

The development of modern infrastructure requires construction materials that combine high mechanical performance, enhanced durability, and ease of placement. In this context, self-compacting concrete (SCC) has represented a major advancement since its emergence in the late 1980s [1]. Owing to its specific rheological properties, SCC exhibits self-flowing behaviour that enables complete filling of formwork, including complex geometries, while providing uniform compaction without mechanical vibration, even in highly reinforced structural elements [2–5]. These characteristics endow SCC with excellent formwork-filling performance, a strong ability to pass through reinforcement, and satisfactory resistance to segregation, all of which are essential for ensuring high-quality placement [6]. Furthermore, the use of SCC improves the homogeneity and surface finish of structures while reducing on-site noise pollution and labour-related costs [7].

However, SCC generally requires high binder and fine contents, which raises growing environmental concerns. The construction sector faces significant challenges related to the intensive use of virgin raw materials and the carbon dioxide (CO_2) emissions generated during the manufacture of cementitious materials. Portland cement production is estimated to contribute approximately 6–10% of global anthropogenic CO_2 emissions, largely due to the decarbonation of limestone during clinker production [8,9]. Therefore, reducing cement content through the use of supplementary cementitious materials (SCMs), together with recycled concrete aggregates (RCA) has become a priority for producing low-impact SCC [10–12].

Recycled coarse aggregates, obtained from the crushing of demolished concrete, represent a relevant solution for the valorisation of construction and demolition waste and for reducing the extraction of natural coarse aggregates (NCA), while also reducing the quantities of waste disposed of in landfill [13–16]. However, their incorporation into self-compacting concrete remains challenging due to their high porosity, water absorption, and adhered residual mortar, which may adversely affect workability, interfacial transition zones (ITZ), mechanical properties, and durability [17–19]. In SCC, these effects may be even more pronounced, since any variation in available water or paste viscosity directly influences flowability, passing ability, and mixture stability.

To mitigate these adverse effects, the incorporation of SCMs represents a particularly relevant strategy, especially since SCC requires a significantly higher fine content than conventional vibrated concrete to ensure high flowability without segregation [7]. SCMs such as silica fume (SF), ground granulated blast-furnace slag (GGBFS), and natural pozzolan (NP) are commonly used as partial replacements for cement, while simultaneously enhancing concrete performance through complementary mechanisms.

SF, characterised by its extremely fine particle size and high pozzolanic reactivity, acts simultaneously as an ultrafine filler, filling the voids within the cementitious matrix and as a reactive pozzolanic material, consuming portlandite and producing supplementary calcium silicate hydrate (C–S–H). This dual action contributes to reduced porosity, improved cohesion of the cement paste microstructure, and enhanced mechanical strength at medium and long curing ages [20–22]. GGBFS, owing to its latent hydraulic activity, promotes prolonged hydration of the binder. Its incorporation improves paste workability, increases matrix compactness, and enhances concrete durability, particularly against chemical attack, by limiting water absorption and fluid transport [23–25].

In addition to industrial by-products, finely pulverised natural pozzolan also exhibits noteworthy pozzolanic reactivity. Its incorporation improves mechanical properties and reduces the transport properties of concrete, particularly permeability and the diffusivity of aggressive agents, thereby enhancing the overall durability of the material [7,26,27]. In this respect, multi-component binder systems appear particularly promising for SCC containing RCA, since suitable combinations of SCMs may partially compensate for the deficiencies commonly associated with recycled aggregates [28].

Beyond construction and demolition waste, recent studies have shown that various industrial, bio-based, and marine wastes can also be successfully incorporated into cement-based materials as aggregates, fillers, or binder substitutes, thereby reducing landfill disposal and virgin resource consumption. Recycled plastic and ceramic industrial waste have already been used in eco-friendly construction materials with satisfactory performance [29]. Cork-based lightweight mortars reinforced with polyethylene fibres have shown reduced density and thermal conductivity while maintaining acceptable mechanical performance [30]. Ceramic waste used as a partial replacement for natural sand in flowable sand concrete was also found to improve mechanical performance up to an optimum substitution level [31]. In highly flowable cement-based materials, granite industrial waste and seashell powder have also shown beneficial effects on compactness and mechanical performance[32,33]. More recently, the combined use of ceramic waste, granite waste, and seashell bio-waste has been proposed as a promising multi-waste strategy for producing high-strength and flowable sand concrete [34]. Although these studies concern waste streams different from RCA, they confirm the growing interest in integrated recycling strategies that improve both sustainability and engineering performance.

In this broader context, quaternary binder systems combining ordinary Portland cement (OPC), SF, GGBFS, and NP appear to be a promising research direction. However, although extensive literature exists on SCC incorporating recycled aggregates or blended binders, these parameters have often been investigated separately or under differing mix-design conditions. As a result, their respective and combined effects remain insufficiently clarified. In particular, limited information is available on the extent to which quaternary binder systems incorporating SF, GGBFS, and NP can compensate for the adverse effects commonly associated with RCA in SCC when key formulation parameters are kept constant.

The novelty of the present work lies in the controlled and structured investigation of the combined influence of aggregate type, namely natural versus RCA, and quaternary binder composition based on OPC, SF, GGBFS, and NP. Unlike many previous studies, the experimental programme was designed using two parallel SCC series produced under identical water-to-powder ratio and superplasticiser dosage, thereby allowing a direct comparison of the individual and interactive effects of these parameters.

This study contributes to the field by providing a direct comparative assessment of the extent to which optimised quaternary binder systems can mitigate the drawbacks of RCA in SCC. It also advances current knowledge by clarifying the coupled effect of aggregate type and quaternary binder composition under controlled formulation conditions. In addition, the combined evaluation of fresh-state, mechanical, ultrasonic, and sorptivity-related behaviour provides a broader interpretation of SCC performance than compressive strength alone.

The main objective of this work is to evaluate the combined influence of coarse aggregate type and quaternary binder composition on the fresh and hardened performance of SCC. More specifically, the study aims to determine whether incorporating SF, GGBFS, and NP can offset the negative effects of RCA while maintaining satisfactory flowability, passing ability, strength development, ultrasonic pulse velocity, and sorptivity performance. The main strengths of the study include the consistency of the experimental design and the multi-criteria evaluation of SCC behaviour. However, the conclusions should be interpreted within the scope of the investigated experimental programme, since only one RCA source was considered, durability-related behaviour was assessed mainly through ultrasonic pulse velocity and sorptivity, and no microstructural analyses were performed.

2. Materials

The materials employed in this study include water, cement, natural fine and coarse aggregates, recycled coarse aggregates (RCA), and mineral additions, specifically silica fume (SF), ground granulated blast-furnace slag (GGBFS), and natural pozzolan (NP), which is of volcanic origin and was extracted from the Beni-Saf deposit in western Algeria, as well as a water-reducing superplasticiser (SP). The experimental programme used a 42.5 MPa class cement as the main binder, in combination with SF, GGBFS, and NP additions. The physico-chemical properties of the cement and supplementary cementitious materials (SCMs) are summarised in Table 1. For the fine aggregate component, natural river sand (0–3 mm) was employed. Two categories of coarse aggregates were used: natural and recycled. The RCA was obtained by crushing concrete blocks and sieving to produce nominal particle size fractions of 3–8 mm and 8–15 mm and was used without additional surface treatment. A photograph of the RCA used in this study is shown in Fig. 1. The coarse aggregate skeleton was obtained by combining the 3–8 mm and 8–15 mm fractions in a mass ratio of 1/3 and 2/3, respectively.

The presence of adhered mortar on RCA led to greater porosity and higher water absorption than in NCA. The characteristics of the aggregates used are detailed in Table 2, while the granulometric curves for the sand, NCA, and RCA are provided in Fig. 2. The SP employed was MEDAFLOW 30, a polycarboxylate ether-based admixture in accordance with EN 934-2 [35]; it is a third-generation high-performance water-reducing admixture.

3. Methodology and experimental programme

The experimental programme investigated the SCC behaviour in both the fresh and hardened states. The main steps of the experimental procedure are presented in Fig. 3. The following subsections outline the corresponding tests and procedures.

Table 1. Physicochemical composition of cement and SCMs

Compound	Cement	Silica Fume	GGBFS	Natural Pozzolan
SiO_2	19.34	> 95	38.10	43.50
Al_2O_3	5.37	< 0.5	8.10	17.20
Fe_2O_3	3	< 1	2	9.50
CaO	61.69	< 0.5	42.2	10.50
MgO	1.80	< 1	4.70	2.98
Na_2O	0.14	-	-	3
K_2O	0.76	-	1.20	1.40
SO_3	2.20	-	0.15	0.90
Loss of ignition	5.03	-	-	2.60
Fineness (cm^2/g)	3200	220.000	3500	4000
Density (g/cm^3)	3.10	2.40	2.85	2.70

Table 2. Characteristics of aggregates used

Properties	Sand	NCA	RCA
Specific density (kg/l)	2.60	2.65	2.44
Apparent density (kg/l)	1.54	1.3	1.22
Absorption (%)	2	1.7	6.8
Sand equivalent (%)	91	–	–

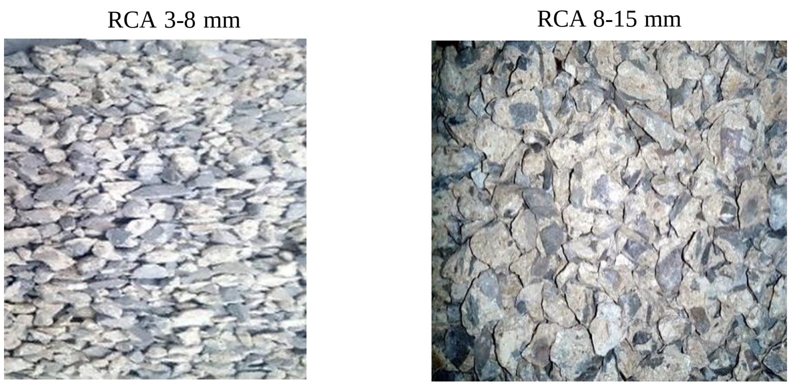

Fig. 1. RCA used in this study

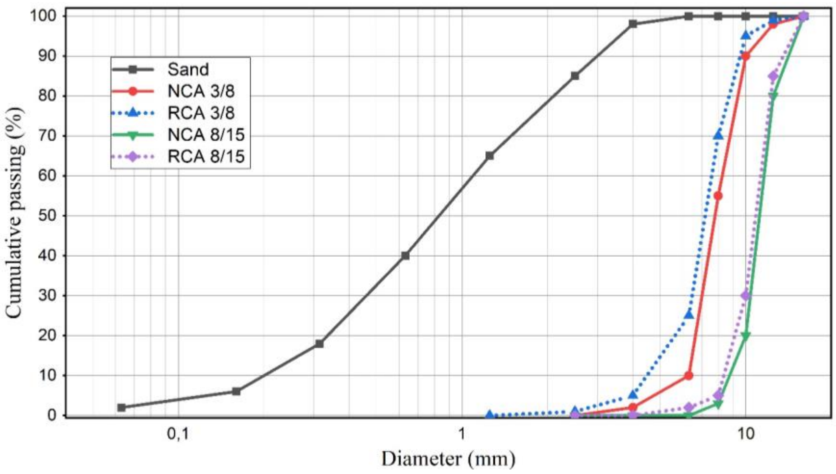

Fig. 2. Particle size distribution curves of fine and coarse aggregates used in the SCC mixtures

3.1. Mixture proportions

Fourteen concrete mixtures were prepared and arranged into two parallel series: seven mixtures with natural aggregates (NSCC) and seven mixtures incorporating recycled coarse aggregates (RSCC). Cement was used as the primary binder in all mixes, while SF, GGBFS, and NP were incorporated as SCMs, introduced as volumetric replacements of cement. Within each aggregate series, a reference mixture without supplementary additions was first established as the Control mixture. A second mixture (N5/0/0 and R5/0/0) was then produced by replacing 5% of the cement with SF. The remaining five mixtures were proportioned with a constant SF content of 5% and a constant total dosage of secondary additions (GGBFS + NP) equal to 20%

of the binder. Under these constraints, the cement fraction was progressively substituted by the GGBFS/NP combination at the following proportions: 20/0, 15/5, 10/10, 5/15, and 0/20. For instance, mixture R5/15/5 was composed of RCA and contained 5% SF, 15% GGBFS, and 5% NP.

All mixtures were prepared using a single water-to-powder ratio of 0.42. The superplasticiser dosage was fixed at 1.2% of binder mass, determined from slump-flow and V-funnel tests, complemented by visual inspection for bleeding. The complete mixture compositions are summarised in Table 3.

The higher water absorption of RCA compared to NCA required additional mixing water in RSCC mixtures. The additional water was calculated as 70% of the difference between the water absorption of RCA (6.8%) and that of NCA (1.7%).

Fig. 3. Main steps of the experimental procedure

Table 3. Mix proportions of the different SCC mixes (kg/m^3)

Mix code		Cement	SF	GGBFS	NP	Water	Sand	NCA	RCA	Additional Water
NSCC	N0/0/0	447	0	0	0	188	840	861	0	0
	N5/0/0	428	17	0	0	187	840	861	0	0
	N5/20/0	342	17	81	0	185	840	861	0	0
	N5/15/5	342	17	61	20	185	840	861	0	0
	N5/10/10	342	17	41	40	185	840	861	0	0
	N5/5/15	343	17	20	60	185	840	861	0	0
	N5/0/20	343	17	0	80	185	840	861	0	0
RSCC	R0/0/0	447	0	0	0	188	840	0	816	29
	R5/0/0	428	17	0	0	187	840	0	816	29
	R5/20/0	342	17	81	0	185	840	0	816	29
	R5/15/5	342	17	61	20	185	840	0	816	29
	R5/10/10	342	17	41	40	185	840	0	816	29
	R5/5/15	343	17	20	60	185	840	0	816	29
	R5/0/20	343	17	0	80	185	840	0	816	29

3.2. Experimental work

The fresh concrete properties were assessed according to the recommendations of the European Federation of National Associations Representing Concrete (EFNARC, 2005) [6]. Filling capacity was evaluated using the slump-flow and V-funnel tests. Passage capacity was measured using the J-ring and L-box tests, and segregation resistance was evaluated using the sieve stability test.

Mechanical performance was evaluated through both destructive and non-destructive methods. Destructive testing comprised flexural strength and compressive strength measurements. Following standard BS EN 12390-5 [36], the flexural tensile strength was determined on 7 × 7 × 28 cm³ prisms at 7, 28, 56, 90, and 120 days. After demolding 24 h after casting, the specimens were cured in water at 20 ± 2 °C until the test date. Compressive strength was subsequently measured at the same ages, on the fragments obtained from the flexural tensile strength test, in accordance with BS EN 12390-3 [37]. Non-destructive evaluation was performed by measuring the ultrasonic pulse velocity (UPV) on companion specimens, as per ASTM C597-02 [38].

Sorptivity provides information about a material's absorption rate. It is quantified at 28 days in accordance with ASTM C1585-4 standard [39], through the sorptivity coefficient, determined from equation (1).

$$S = \frac{Q}{A\sqrt{t}} \qquad (1)$$

where: S – is the coefficient of sorptivity (cm/sec$^{0.5}$), Q – is the volume of water absorbed (cm³), A – is the contact surface area of the specimen (cm²), and t – is the exposure time to water (s).

Prior to sorptivity testing, the samples were preconditioned according to the AFREM–AFPC (1997) procedure.

Each reported value corresponds to the average of three specimens for compressive and flexural strength tests. For UPV and sorptivity, each measurement was calculated as the mean of two specimens.

4. Results and discussion

4.1. Fresh properties of SCC

4.1.1. Slump flow

Figure 4 presents the slump flow diameters of SCC mixtures incorporating NCA and RCA. The measured values (600–750 mm) satisfy the EFNARC requirements [6]. The inclusion of 5% SF resulted in the highest slump flow values (N5/0/0 and R5/0/0), indicating that, at this dosage, SF did not adversely affect flowability. This observation is consistent with previous studies [40,41]. Although SF has a very high specific surface area, which may increase the system's water requirement and potentially reduce the filling ability of SCC, this effect can be compensated for by adjusting the water/binder ratio [28]. The gradual replacement of GGBFS with NP slightly reduced the slump flow of both NCA- and RCA-based mixtures, in agreement with [42]. Similar trends have been reported for high contents of NP [43]. This reduction was less pronounced in RCA mixtures, as the additional water introduced to compensate for RCA absorption mitigated the effect of NP on flowability.

Finally, RSCC presented higher slump flow values than NSCC, mainly due to the greater amount of free water available during the early stage of mixing, in agreement with [23].

4.1.2. Slump-flow time (T_{500})

The T_{500} values (see Fig. 4) lie within the range 2–5 s recommended by EFNARC [6]. The incorporation of SF increased the T_{500} time for mixtures with NCA, from 2.35 to 2.90 s, primarily owing to its higher fineness, whereas it slightly decreased the T_{500} time for mixtures with RCA, from 2.30 to 2.15 s, which can be explained by the higher water content. The incorporation of 20% GGBFS reduced the T_{500} time (NCA: 2.73 s; RCA: 2.10 s), in agreement with [44]. The gradual replacement of GGBFS with NP led to a reduction in viscosity, owing to improved particle packing and enhanced paste lubrication at moderate replacement levels (15% GGBFS + 5% NP to 10% GGBFS + 10% NP), resulting in minimum T_{500} values (NCA: 2.20–2.25 s; RCA: 2.00–2.05 s). Beyond 15% of NP, the increase in water demand and the angular particle morphology of NP particles caused an increase in T_{500} (NCA: 2.95 s; RCA: 2.57 s).

In general, RCA-based mixtures exhibited lower T_{500} values than the corresponding NCA mixtures, reflecting faster flow behaviour associated with the additional water added to compensate for RCA absorption [28].

The difference in T_{500} evolution was mainly observed in the reference mixtures and in those containing only SF, namely N0/0/0 and N5/0/0 in the NSCC series, and R0/0/0 and R5/0/0 in the RSCC series. In the absence of GGBFS and NP, T_{500} was mainly governed by the aggregate type, the additional water added to the RSCC mixtures, and the rheological effect of SF, which influences the cohesiveness and apparent viscosity of the paste.

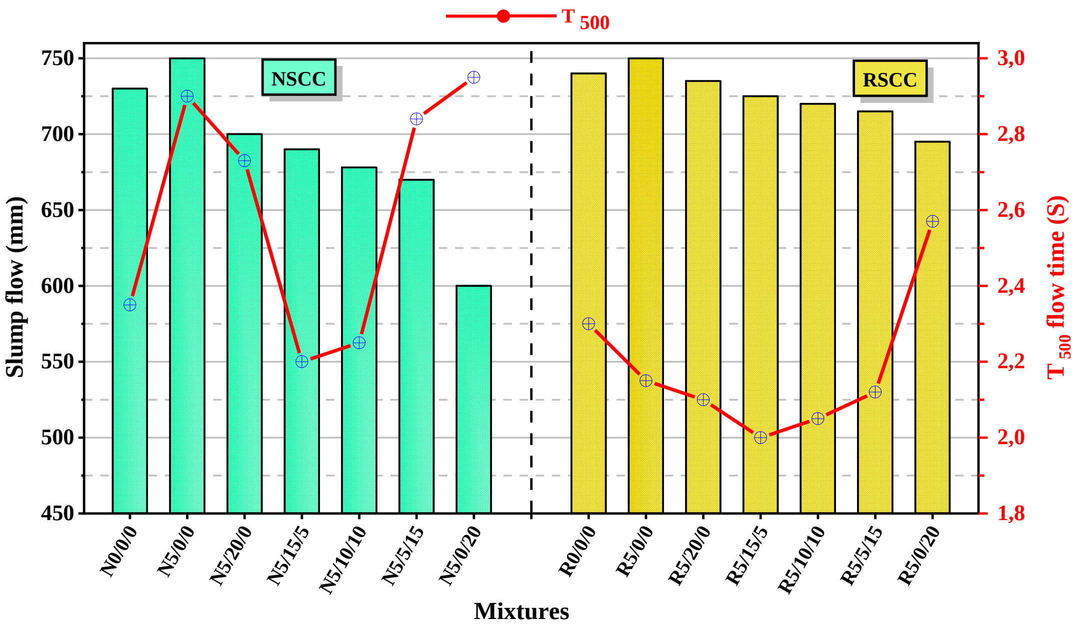

Fig. 4. Slump-flow diameter and T500 time of NSCC and RSCC mixtures

4.1.3. J-Ring test

To assess the mixture's passing ability, the–J-Ring test was performed. According to the ASTM C1621/C1621M standard [45], the difference between the slump flow diameter (SF_d) and the J-ring flow diameter (JF_d) (see Fig. 5) must be less than 50 mm; all mixtures met this requirement. The introduction of 5% SF had different effects depending on the aggregate type. For mixtures with NCA, the SF_d–JF_d value increased from 15 mm (N0/0/0) to 28 mm (N5/0/0), indicating a slight reduction in passing ability, which is associated with increased viscosity [23]. Conversely, for mixtures with RCA, SF reduced the SF_d–JF_d value from 30 mm (R0/0/0) to 25 mm (R5/0/0), suggesting improved cohesion and reduced sensitivity to segregation [21]. The incorporation of 20% GGBFS enhanced passing ability, mainly due to a reduction in interparticle friction. The gradual substitution of GGBFS with NP at levels of (5–10%) further improved passing ability, with optimal performance observed for mixtures N5/15/5 and R5/15/5. At higher replacement levels, the increased water demand and angularity of NP gradually impaired the passing ability.

Overall, the replacement of NCA with RCA led, in the control mixture, to a marked increase in the SF_d–JF_d difference, from 15 mm to 30 mm, indicating a reduction in passing ability, mainly due to the higher roughness, increased porosity, and the presence of adhered mortar on the RCA. In contrast, after the incorporation of SCMs, the SF_d–JF_d values of the NSCC and RSCC mixtures became globally comparable, with differences limited to only 1–4 mm. This evolution shows that the initially adverse effect of RCA on passing ability can be largely mitigated by an appropriate mix design combining additional water and SCMs.

The evolution of the SF_d–JF_d difference followed a trend similar to that observed for the T_{500} time, for the same reasons.

4.1.4. V-funnel flow time

The V-funnel test evaluates the viscosity and filling ability of SCC. Figure 5 shows the flow times measured for the different mixtures passing through the funnel. The recorded times range from 5.11 s to 9.75 s, in accordance with EFNARC recommendations [6]. Replacing 5% of cement with SF reduced the V-funnel flow time of concrete containing NCA by approximately 30% compared with the reference mixture, in agreement with [46], whereas the effect was limited for mixtures with RCA. The incorporation of 20% GGBFS increased the V-funnel time for mixture N5/20/0 compared with N5/0/0, because SF fills the interstitial voids between cement and GGBFS particles, leading to a denser mixture matrix. Conversely, for the RCA series, the V-funnel time decreased when comparing R5/20/0 to R5/0/0, due to the higher water content. Substituting GGBFS with 5% NP yielded the minimum flow times (6.20 s for N5/15/5 and 5.11 s for R5/15/5), owing to the improved particle-size distribution in the ternary system. Increasing the NP content beyond these replacement levels significantly impaired flowability (e.g., 9.75 s for N5/0/20 and 8.10 s for R5/0/20), which can be attributed to the increased water demand and the negative rheological effects of NP [26,47].

Excluding the binary mixtures, SCC incorporating RCA generally exhibited lower V-funnel times than the corresponding NCA mixtures, which is consistent with the effect of the additional water content.

The evolution of the V-funnel flow time exhibited a trend similar to that of the T_{500} time, reflecting the influence of the same underlying factors.

4.1.5. L-box test

Figure 6 shows that the H_2/H_1 ratio measured by the L-box test ranges between 0.83 and 0.95, in accordance with EFNARC recommendations [6], with no blocking observed. The addition of SF improved the passing ability of SCC, incorporating both NCA and RCA, due to its filler effect. The substitution of GGBFS with NP at levels of 5–10% further enhanced passing ability, with an optimum observed for the 5/15/5 mixture (NCA: 0.93; RCA: 0.95), owing to the synergistic interaction between GGBFS and NP. Above this range, the H_2/H_1 ratio declined, indicating a more viscous mixture. These reductions may be attributed to the high porosity and large specific surface area of the NP.

The L-box results confirm the trend observed in the J-ring test: mixtures containing RCA generally exhibited slightly better passing ability near obstacles [21], mainly due to the additional free water. This effect became less pronounced in ternary and quaternary mixtures, where SCMs contributed to a more cohesive and denser paste.

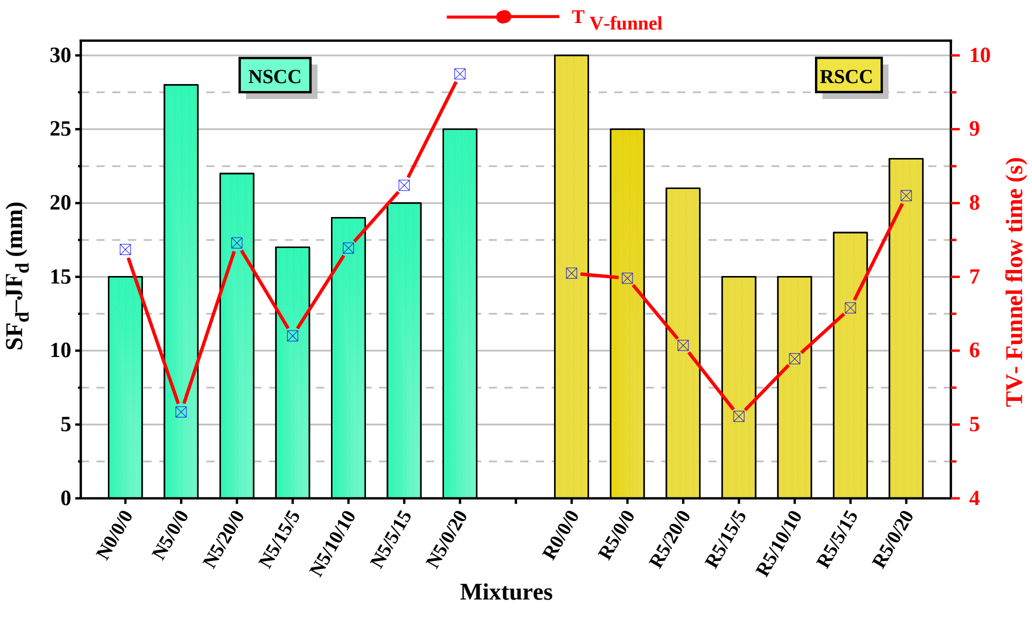

Fig. 5. SFd-JFd difference and V-funnel time of NSCC and RSCC mixtures

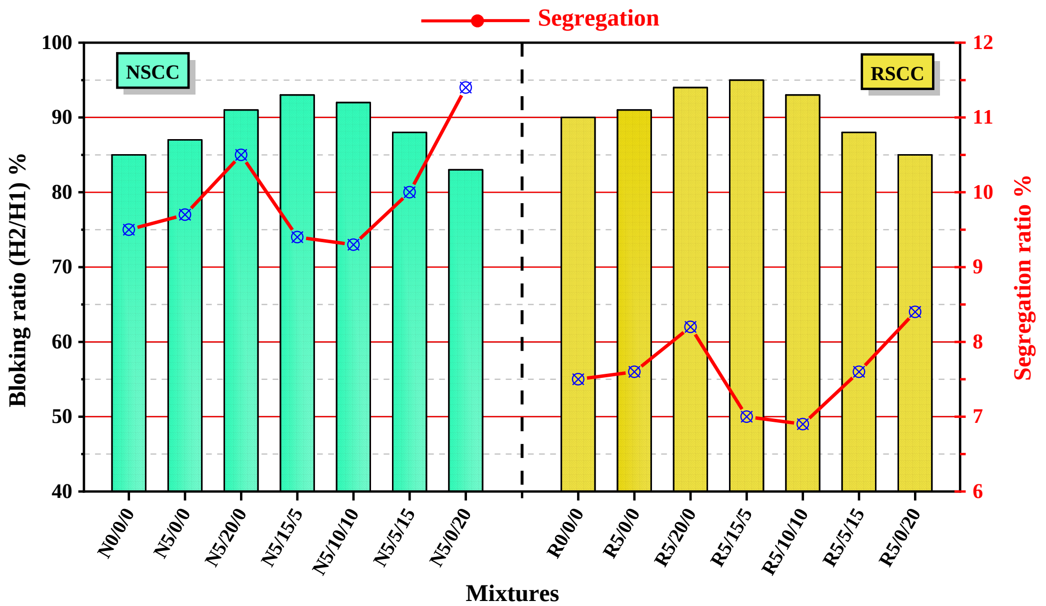

Fig. 6. Blocking ratio (H2/H1) and segregation ratio of NSCC and RSCC mixtures

4.1.6. Segregation resistance

This test evaluates the ability of SCC to maintain its homogeneity from casting until the onset of setting. The bleeding percentages (see Fig. 6) range from 6.4% to 11.4%, classifying all mixtures in the SR2 category (<15%), in accordance with EFNARC [6], and indicating satisfactory resistance to segregation. The incorporation of SF increased the bleeding percentage by 2.1% and 1.3% for mixtures with NCA and RCA, respectively, while the substitution of 20% GGBFS increased it by 8%. Partial replacement of GGBFS with NP (5–10%) reduced bleeding, with the lowest values observed in mixtures N5/15/5 and R5/15/5, followed by an increase at higher NP contents.

Moreover, replacing NCA with RCA reduced bleeding, as the rough surface texture and high water absorption of RCA increased the apparent viscosity and limited the upward migration of fines. The results are consistent with those reported in [41,48,49].

4.2. Hardened properties of SCC

4.2.1. Compressive strength

Figure 7 illustrates the evolution of compressive strength (Cs) for the two types of concrete studied at different curing ages, showing that Cs increases with curing time. The incorporation of 5% SF in SCC mixtures with NCA exhibited a characteristic dual behaviour, consisting of an initial reduction in strength at 7 and 28 days, followed by a marked improvement beyond 56 days. Specifically, the N5/0/0 mixture showed a Cs value 17% lower than that of the reference mixture N0/0/0 at 7 days, in agreement with the findings reported in [41], but exceeded it by 12% at 120 days, reaching 58.36 MPa. Moreover, [50] reported that mixtures incorporating 3–6% SF exhibited higher Cs than those without SF. This phenomenon stems from the delayed pozzolanic reaction of SF, which enhances microstructural refinement by producing additional calcium silicate hydrate (C−S−H) phases. In contrast, in the RCA mixtures, the incorporation of 5% SF improved compressive strength from the earliest curing age. However, the effect was less pronounced in mixtures containing RCA, which may be attributed to their inherently porous nature and the presence of fragile interfacial transition zones (ITZ), as reported in [51].

The incorporation of GGBFS at a 20% replacement level reduced the Cs of both blends, particularly at early ages. However, in the long term (56 to 120 days), the Cs values became close to those of reference concretes, as also reported by [52].

The subsequent replacement of GGBFS with NP generated promising synergies, particularly for the N5/15/5 formulation, which showed the most regular strength development and reached 54.1 MPa at 120 days. The superiority of this optimised formulation was also observed in the RCA series, where the R5/15/5 mixture achieved the highest Cs (48.9 MPa at 120 days), highlighting the binder system's ability to effectively compensate for the limitations of RCA. In contrast, the R5/10/10 mixture consistently yielded the lowest strength values, confirming the sensitivity of performance to the ternary formulation's balance of proportions.

The Cs values of mixtures incorporating RCA were lower than those of mixtures with NCA, in agreement with previous studies [17,53,54], which also attributed this behaviour to the poor mechanical quality, the presence of porosity and enhanced water absorption of RCA compared to NCA, as well as to their altered microstructure, characterised by a porous adhered mortar and a low ITZ. Nevertheless, ternary and quaternary RSCC were less affected by changes in aggregate type, indicating that the synergistic effects of SCMs helped reduce the performance gap between NCA- and RCA-based concretes.

After approximate conversion to equivalent cylinder strength, the concretes investigated at 28 days generally met the minimum thresholds specified in Table 19.2.1.1 of ACI 318. This indicates that the proposed mixtures remain compatible with conventional structural concrete applications from a compressive-strength standpoint.

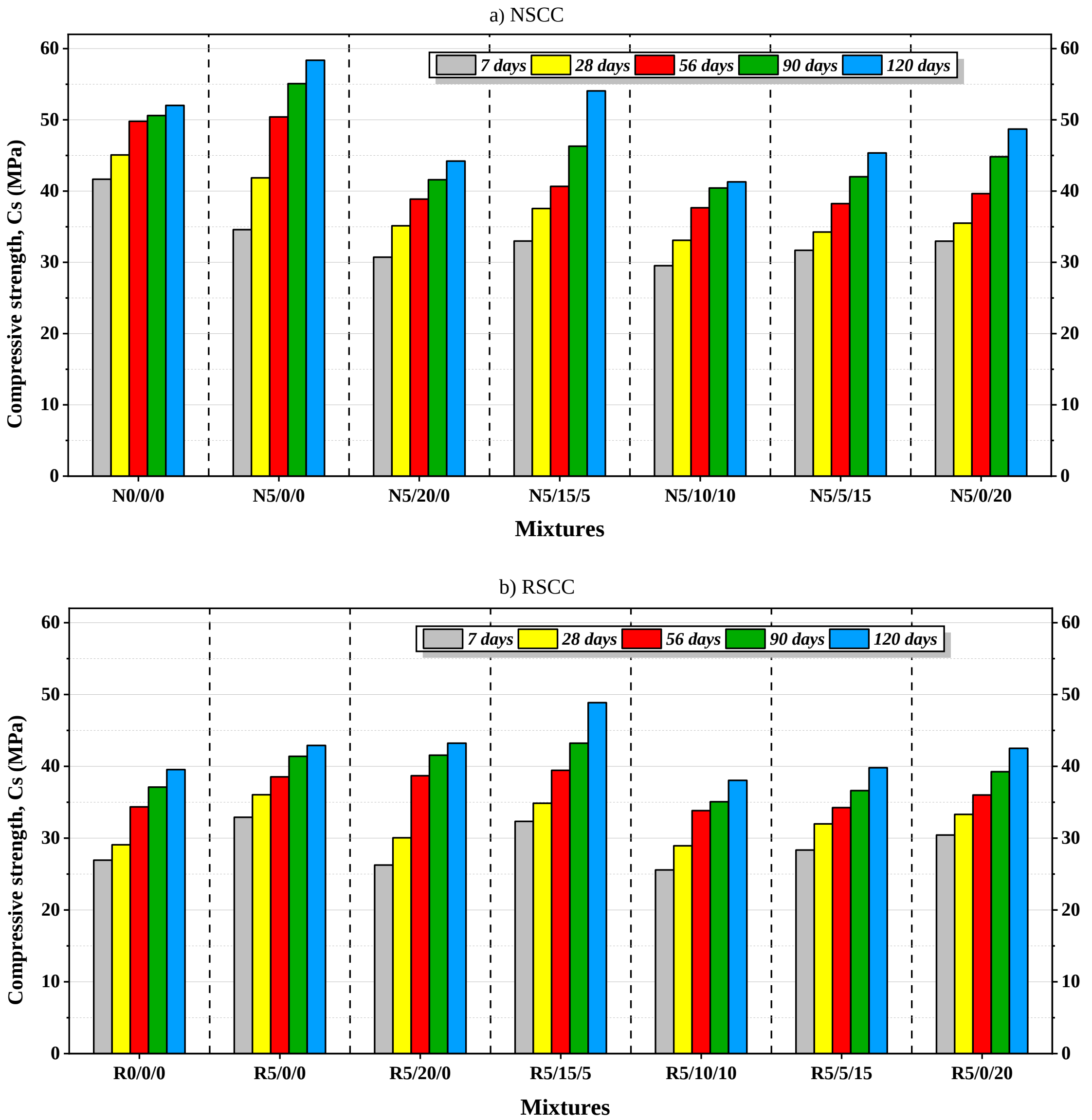

Fig. 7. Evolution of compressive strength of NSCC and RSCC mixtures

4.2.2. Flexural strength

The flexural tensile strength values obtained at curing ages of 7, 28, 56, 90, and 120 days for the different mixtures investigated are presented in Fig. 8. For mixtures based on NCA, the reference mixture N0/0/0 displayed the highest strengths in the short term (7 and 28 days), owing to the contribution of clinker to early hydration and strength development. However, the N5/0/0 mixture developed higher strengths than the reference N0/0/0 mixture from 56 days onward, due to the pozzolanic reaction of SF, which densifies the cementitious matrix and improves the ITZ. In contrast, the N5/0/20 mixture exhibited the lowest values at all ages, which can be attributed to its high NP content, as observed in [42]

In the RCA series, the R5/0/0 mixture showed the highest flexural strengths, suggesting that SF helped mitigate the adverse effects of RCA by improving the ITZ and correcting defects associated with the old adhered mortar, as reported in [51]. The R5/0/20 mixture remained the least resistant within its series for the same reasons, whereas the quaternary mixture R5/15/5 achieved the second-highest strength, suggesting an optimal combination of GGBFS and NP at the 15%–5% replacement levels.

The transition from NCA to RCA at a constant mineral addition composition was characterised by a systematic loss of flexural strength, linked to the higher porosity and lower ITZ quality of RCA. Despite this reduction, the beneficial effect of SCMs remained evident, as the performance gap was significantly reduced in mixtures containing balanced blended binders. By contrast, [55] found that, without SCMs, the 28-day flexural strength of SCC made with NCA remained comparable to that of concrete made with RCA. Furthermore, the addition of SF improved the flexural strength of the NCA-based concrete relative to the control mixture.

Overall, the flexural-strength results followed the same general trend as the compressive-strength results, confirming the positive influence of matrix densification and interfacial enhancement on tensile behaviour. These findings are consistent with the general empirical approach adopted in ACI 318 (Section 19.2.3), where flexural behaviour is related to compressive strength, since mixtures with higher compressive strength generally also exhibited better flexural performance.

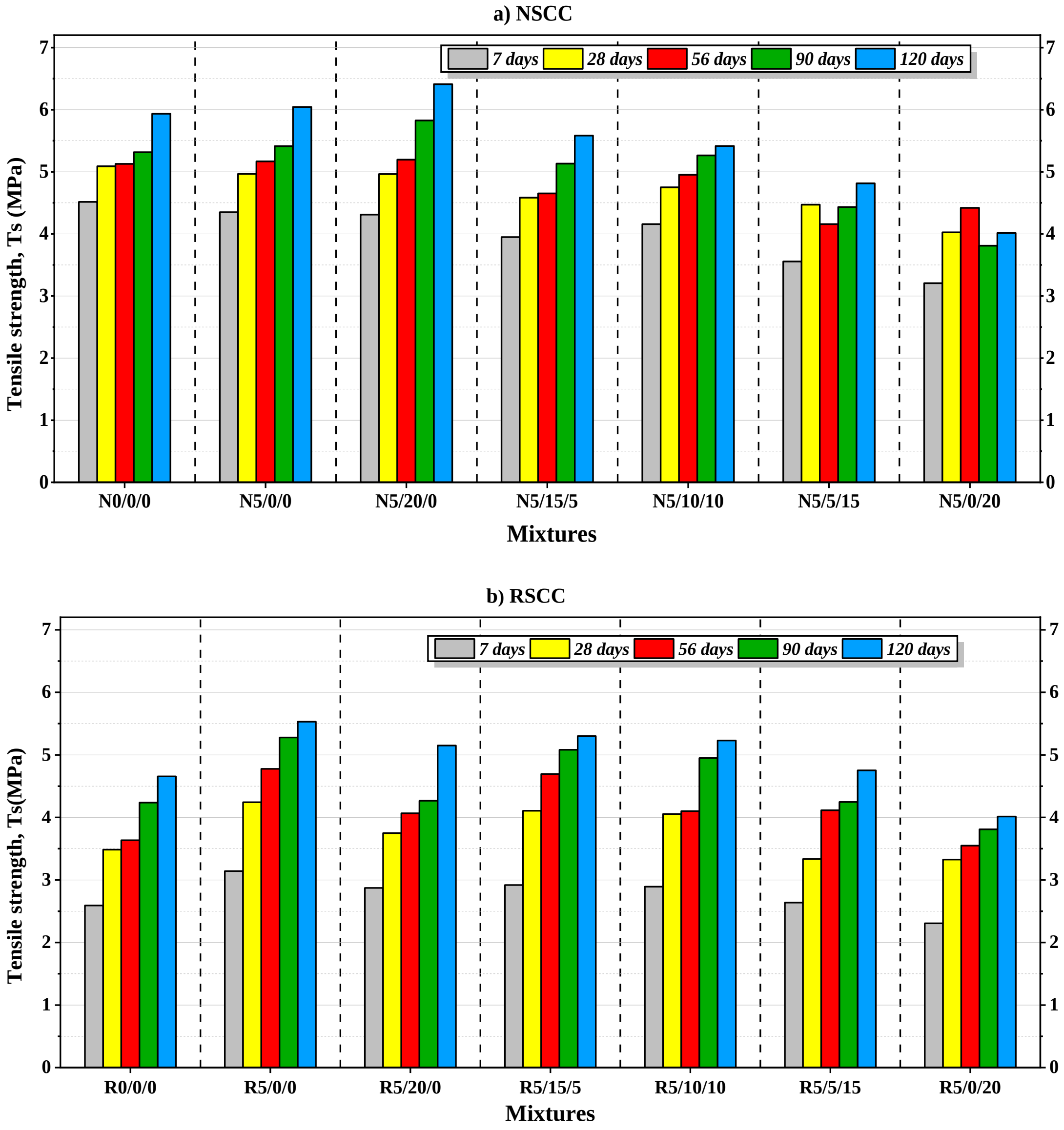

Fig. 8. Evolution of flexural tensile strength of NSCC and RSCC mixtures

4.2.3. Ultrasonic Pulse Velocity (UPV)

The results obtained from UPV tests conducted on both types of concrete at a curing age of 28 days are shown in Fig. 9. The measured UPV values for all concrete mixtures range between 3.758 and 4.600 km/s. Except for the N5/0/0 mixture, which falls within the excellent category, all other mixtures are classified as good-quality according to the criteria proposed in [56].

The highest UPV values for both types of concrete correspond to mixtures containing only SF as a SCM. This confirms that SF reduced porosity and densified both the paste and the ITZ owing to its extremely fine particle size and pozzolanic reactivity. The 5/15/5 formulation exhibited the highest UPV values among the ternary and quaternary mixtures for both concrete types, making this combination the optimal in its series. By contrast, increasing the NP content progressively reduced the UPV values in both concrete types.–The higher ultrasonic pulse velocity values measured for mixtures incorporating optimised SCM combinations are consistent with their improved Cs, indicating reduced internal defects and enhanced matrix compactness.

According to the results, replacing NCA with RCA reduced UPV across all mixtures, with decreases ranging from 4.5% to 11%. As reported in [57], the reduction in pulse velocity in RSCC mixtures is mainly related to the presence of significant voids within the aggregates and to weaker adhesion between RCA and the cementitious matrix.

The UPV classification given in ACI 228.2R (quality table) is consistent with the classification previously cited from IS 13311-1 (1992) [56].

4.2.4. Sorptivity Coefficient of SCC

The sorptivity test quantifies the rate of capillary water ingress into unsaturated specimens brought into contact with water under no hydraulic pressure. A high absorption capacity indicates that the material is prone to rapid liquid ingress. The sorptivity values are presented in Fig. 10.

Adding 5% SF resulted in a marked decrease in sorptivity for both types of concrete, due to its ability to densify the interfacial transition zone through its filler effect. These results agree with [54]. The progressive replacement of cement with GGBFS and NP reduced the sorptivity of concretes made with NCA. In contrast, for concretes containing RCA, an optimum behaviour was observed for the formulation incorporating 15% GGBFS and 5% NP.

The inverse relationship between compressive strength and sorptivity suggests that mixtures with higher long-term strength exhibit a denser pore structure, which limits capillary water transport. This effect is particularly pronounced for the optimised quaternary binder, highlighting the synergistic role of SF, GGBFS, and NP in refining the cementitious matrix. Conversely, high NP content combined with low GGBFS content resulted in a significant increase in sorptivity. This behaviour may be attributed to the delayed pozzolanic reactivity of NP, which can leave a still-connected capillary pore network at 28 days.

Finally, the results confirm that NSCC exhibits a lower sorptivity coefficient than RSCC, which is attributed to the inferior quality of RCA and to the more porous microstructure associated with adhered mortar.

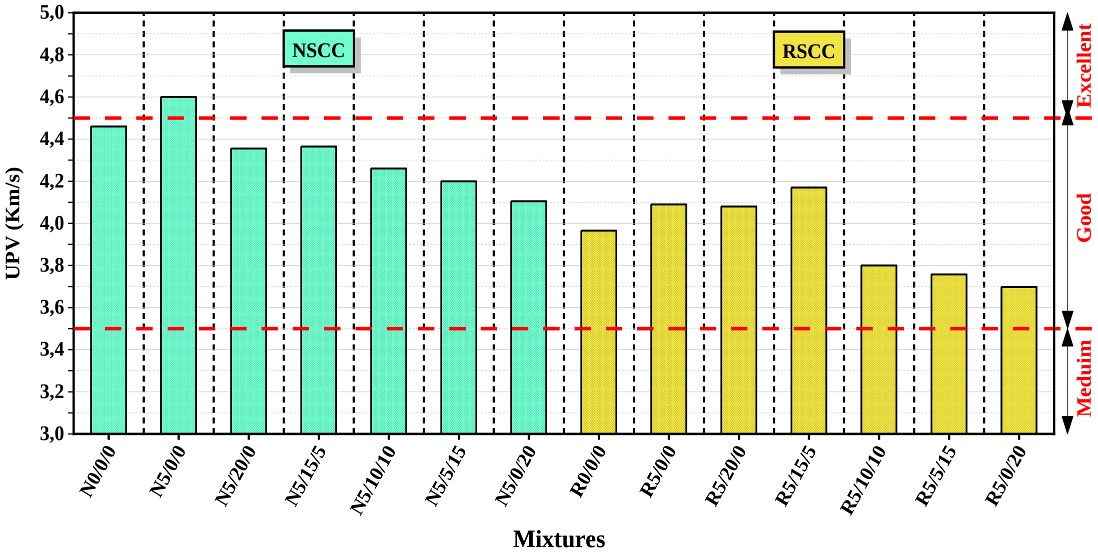

Fig. 9. Ultrasonic pulse velocity (UPV) of NSCC and RSCC mixtures at 28 days

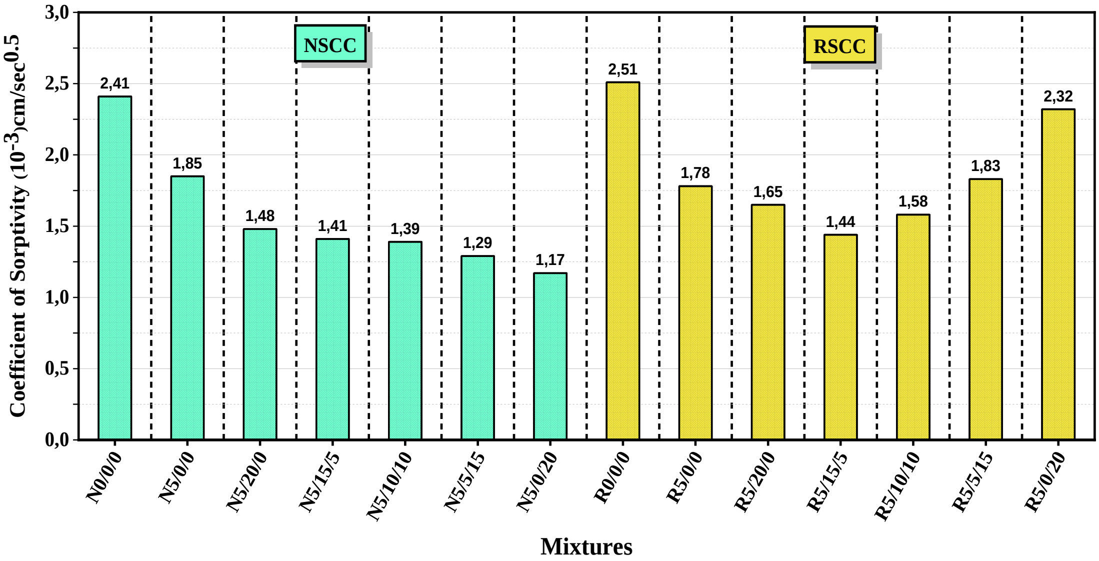

Fig. 10. Sorptivity coefficients of NSCC and RSCC mixtures measured at 28 days

5. Conclusion

This research investigates the feasibility of producing sustainable SCC by combining RCA with a blend of SCMs, specifically SF, GGBFS, and NP. The main findings are summarised as follows:

1. All SCC mixtures, whether prepared with NCA or RCA satisfied the EFNARC requirements for filling ability, passing ability, and segregation resistance. This indicates that SCC incorporating RCA can be successfully produced, provided that the higher water absorption of RCA is properly accounted for in the mix design.
2. The use of RCA generally led to lower hardened performance compared with the corresponding NCA mixtures. For the reference concrete, the compressive strength at 120 days decreased from 52.03 MPa for N0/0/0 to 39.55 MPa for R0/0/0. Despite this reduction, the results also showed that binder composition played a major role in improving the overall behaviour of the mixtures.
3. Among the investigated formulations, the mixture containing 5% SF, 15% GGBFS, and 5% NP showed the most balanced performance. At 120 days, it reached 54.07 MPa in the NCA series and 48.86 MPa in the RCA series, while also exhibiting lower sorptivity. More broadly, the

use of optimized blended binders helped reduce the performance gap between NCA- and RCA-based concretes. In terms of compressive strength at 120 days, the reduction associated with the use of RCA was 23.99% for the reference mixture, but this difference decreased to 9.64% for the 5% SF–15% GGBFS–5% NP mixture and to 2.24% for the 5% SF–20% GGBFS mixture.

4. The ultrasonic pulse velocity values obtained at 28 days, ranging from 3.758 to 4.600 km/s, further indicated generally good to excellent internal concrete quality. These results support the view that suitably proportioned SCM combinations can improve the compactness and overall quality of SCC, even when RCA is used.

Overall, the findings demonstrate that the combined use of RCA and carefully selected SCMs represents a promising approach for developing more sustainable SCC. Although incorporating RCA tends to reduce mechanical performance, this limitation can be significantly mitigated through an appropriate binder design. The study, therefore, highlights the potential of multi-SCM systems to support the use of recycled aggregates in SCC intended for conventional structural applications.

Future research should focus on the long-term durability of these mixtures under aggressive exposure conditions, particularly chloride ingress, carbonation, and sulphate attack. Additional microstructural investigations would also be useful to better understand the combined effects of SF, GGBFS, and NP, especially in mixtures containing RCA. Furthermore, larger experimental datasets with more replicates are needed to allow more robust statistical analysis.

Conflict of interest

The authors declare that they have no conflict of interest.

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