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Research Article

Influence of sanitary ceramic fillers on the mechanical and bond performance of self-compacting sand concrete for structural repair

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Abstract

The construction industry faces increasing pressure to reduce its environmental impact and promote the valorization of industrial waste. In this context, this study examines the influence of progressively replacing limestone fillers (LF) with sanitary ceramic fillers (SCF) on the properties of self-compacting sand concrete (SCSC) designed for structural repair applications. Five concrete mixtures were produced with substitution rates of 0%, 25%, 50%, 75%, and 100%, allowing a progressive evaluation of the influence of sanitary ceramic fillers across the entire replacement range. The fresh-state behavior was evaluated using mini-slump flow and V-funnel tests, while mechanical performance was assessed through compressive and flexural strength tests at 7, 28, 90, and 180 days. The bond strength between the SCSC and the substrate was determined by the pull-off test which represents a key parameter for evaluating the durability and reliability of concrete repair systems. The results indicate that increasing the SCF substitution rate reduces flowability, with the mini-slump flow decreasing from 26.5 cm to 22.8 cm (≈14% reduction), while the V-funnel flow time increased from 7.2 s to 12.5 s. Mechanical strengths exhibit a nonlinear evolution with the substitution ratio, with significant improvements observed at higher substitution levels. The incorporation of SCF also influenced the bond behavior with the substrate. While the C50 formulation showed an intermediate response reflecting microstructural adjustments at moderate substitution levels, the C100 mixture achieved the highest overall mechanical and bond performance among all investigated formulations. These findings demonstrate that sanitary ceramic waste can be effectively used as an alternative filler in SCSC for structural repair applications, contributing both to sustainable waste valorization and to the development of high-performance repair materials.

1. Introduction

The construction industry faces a dual challenge: reducing its environmental footprint while improving the durability of infrastructure. The construction sector is responsible for a significant share of global CO_2 emissions, with cement production alone accounting for nearly 7–8% of global anthropogenic CO_2 emissions. This environmental burden highlights the urgent need for more sustainable construction materials and practices. The valorization of industrial waste as alternative components in cementitious materials represents a promising approach consistent with the principles of the circular economy [1,2]. In this context, self-compacting concrete (SCC), and more specifically self-compacting sand concrete (SCSC), has attracted growing interest in

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recent decades. These concretes, which are free of coarse aggregates, are characterized by excellent flowability and filling capacity in complex formworks, properties that make them particularly suitable for structural repair applications [3–5]. Compared with conventional repair mortars, SCSC offers improved flowability, better filling ability in confined zones, and easier casting without vibration, which makes it particularly advantageous for structural repair works.

The formulation of SCSC typically requires a high proportion of fine particles, usually in the form of limestone fillers (LF), to ensure stability and self-compacting behavior [6,7]. Although widely available and economical, the extraction and grinding of limestone fillers still generate additional environmental burdens, particularly in terms of energy consumption, natural resource use, and associated CO_2 emissions [8]. At the same time, the sanitary ceramics industry generates large amounts of waste each year, consisting mainly of rejected or defective products from manufacturing processes. These wastes represent an underutilized mineral resource and are commonly landfilled despite their high silico-aluminous content. These ceramic wastes, rich in silica and alumina, show strong potential for valorization in cementitious matrices due to their mineralogical structure and potential pozzolanic reactivity [9–11]. Recent studies have further confirmed the potential of recycled ceramic materials for the development of sustainable cementitious composites and repair applications [41–44].

Several studies have investigated the use of ceramic waste in cement-based materials, mainly as a partial replacement for cement or natural aggregates [12–14]. It has been shown that partial substitution of cement with ceramic powders can improve the long-term strength and durability of concrete [15,16]. Similarly, the use of crushed ceramic aggregates as substitutes for natural aggregates has been found to be technically feasible, with comparable mechanical performance [17]. Nevertheless, these studies mainly addressed ceramic waste as a cementitious addition or aggregate substitute, while its specific role as a filler in self-compacting sand concrete remains insufficiently documented. Consequently, only a limited number of studies have investigated the incorporation of ceramic waste as fillers in SCSC for structural repair applications, and even fewer have examined its influence on rheological behavior and on the quality of the interfacial transition zone (ITZ) [18,19]. Bond strength between the repair material and the existing substrate is a critical factor governing the long-term performance of repair works [20–22]. The roughness of the interface, mechanical compatibility, and the porosity of the interfacial transition zone (ITZ) are key parameters influencing this bond [23]. The use of pozzolanic materials in repair formulations can enhance this interface by densifying the microstructure through the consumption of portlandite [24]. In the case of sanitary ceramic fillers (SCF), their angular morphology may promote better mechanical interlocking, while their silico-aluminous composition may contribute to improving the interfacial microstructure [25]. To the authors' knowledge, no previous investigation has addressed sanitary ceramic fillers as a direct substitute for limestone fillers in self-compacting sand concrete (SCSC) across the full substitution range (0–100%), nor jointly evaluated their effects on fresh-state rheology, medium- and long-term mechanical performance (up to 180 days), and bond strength with the substrate in a structural repair context.

The present study aims to fill this gap and thereby provide new experimental evidence supporting the valorization of sanitary ceramic waste as a sustainable filler for repair-oriented SCSC. Beyond this central gap, two additional aspects also remain insufficiently resolved in the literature:

- The progressive, potentially non-linear influence of the LF→SCF substitution ratio on the rheological behavior of SCSC [27], particularly at high substitution levels where the medium- and long-term mechanical response is still poorly documented [26,28], and the resulting bond performance between the repair material and the existing substrate remains largely unexplored [29];
- The microstructural evolution of the interfacial transition zone (ITZ) when sanitary ceramic fillers are incorporated into SCSC for structural repair, which has not yet been sufficiently clarified.

To address these gaps, the present study aims to evaluate the effect of the progressive substitution of limestone fillers by sanitary ceramic fillers (0%, 25%, 50%, 75%, and 100%) on the fresh and hardened properties of SCSC. The specific objectives are to:

- Characterize the influence of the substitution rate on the fresh-state rheology of SCSC;
- Examine the evolution of compressive and flexural strengths at 7, 28, 90, and 180 days;
- Assess the effect of substitution on bond strength with the substrate in a structural repair context;
- Identify optimal substitution ratios that balance technical performance with environmental benefits.

The scientific contribution of this work is threefold: (i) it provides the first systematic experimental dataset on the full-range substitution (0–100%) of limestone fillers by sanitary ceramic fillers in self-compacting sand concrete, covering fresh-state rheology, medium- and long-term mechanical performance, and bond strength with the substrate; (ii) it delivers quantitative evidence on the adhesion behavior of SCSC repair layers to ordinary concrete substrates, an aspect rarely addressed in the literature; and (iii) it offers practical guidance for the formulation of sustainable, repair-oriented SCSC, contributing to the valorization of sanitary ceramic waste within a circular-economy framework.

2. Materials and Methods

2.1. Materials Used

2.1.1. Cement

Two types of cement were used in this study in order to reproduce realistic repair conditions, both conforming to NF EN 197-1 [47]. A CEM I 52.5 N cement with a Blaine fineness of 4523 cm^2/g was employed for preparing the repair concrete mixtures, due to its higher early strength and rapid hydration characteristics. For the substrate (ordinary concrete), a CEM II/B 42.5 N cement with a fineness of 3700 cm^2/g was used, which is commonly applied in conventional structural concrete. The CEM I was supplied by GICA INDJAZAT from the Chlef cement plant, while the CEM II/B was provided by the Lafarge plant located in Okaz, Mascara (Algeria). The chemical and mineralogical compositions of both cements are summarized in Table 1.

2.1.2. Limestone Fillers (LF)

The limestone fillers used in this study were prepared from natural limestone rocks rich in calcium carbonate. The preparation procedure was carried out following a controlled, reproducible protocol consisting of the following steps:

- Raw material selection: natural limestone gravels of the 3/8 mm fraction were collected and used as a starting material.
- Grinding: the selected gravels were ground in a laboratory ball mill for 30 minutes.
- Sieving: the obtained powder was passed through a 200 μm mesh to eliminate coarse particles.
- Fineness control: the fineness of the final product was verified using a 45 μm sieve, with a target retained fraction of approximately 25%, ensuring a particle size distribution consistent with that of the sanitary ceramic fillers described in Section 2.1.3.

The resulting limestone filler is characterized by a high $CaCO_3$ content, a significant loss on ignition (43.2%), and a density of 2.63 g/cm^3. Its Blaine fineness is 4200 cm^2/g, with a median particle size (d_{50}) of approximately 50 μm.

2.1.3. Sanitary Ceramic Fillers (SCF)

The sanitary ceramic fillers were produced from defective sanitary ware (washbasins and toilet bowls) following a controlled multi-step preparation procedure, designed to obtain a fineness comparable to that of the limestone fillers in order to isolate the effect of the chemical nature of the filler from any granulometric influence:

- Selection and cleaning: large fragments of defective sanitary ware were selected, manually cleaned, and washed to remove surface contaminants.
- Drying: the cleaned fragments were oven-dried at 105 °C for 24 hours to eliminate residual moisture.

- Pre-crushing: the dried fragments were reduced using a laboratory jaw crusher and screened through an 8 mm sieve to obtain a homogeneous coarse fraction.
- Grinding: the pre-crushed material was further processed in a laboratory ball mill for 60 minutes. The longer grinding duration compared with limestone (60 min vs. 30 min) was selected to compensate for the higher hardness of the ceramic material and to achieve a comparable fineness between the two fillers.
- Sieving: the ground powder was passed through a 200 µm mesh.
- Fineness control: the fineness was verified using a 45 µm sieve, targeting the same retained fraction of approximately 25% as for the limestone fillers.

Fig. 1. Limestone fillers (LF) and sanitary ceramic fillers (SCF) in their raw and ground states

The resulting sanitary ceramic filler is characterized by a mainly silico-aluminous chemical composition, a low loss on ignition (1.46%), and a density of 2.53 g/cm^3. Its Blaine fineness is 3800 cm^2/g, and the median particle size is close to 20 µm. The angular morphology of the obtained ceramic particles may influence the rheological behavior of the fresh mixtures and could contribute to mechanical interlocking at the repair interface, while a possible pozzolanic contribution related to the high silica and alumina contents cannot be ruled out and would require dedicated microstructural investigation.

Figure 1 illustrates the visual appearance of the two fillers used in this study, before and after grinding:

- The top row shows the raw materials crushed limestone gravels (3/8 mm fraction, LF) on the left, and pre-crushed sanitary ceramic fragments (≤ 8 mm, SCF) on the right — highlighting the rounded morphology of the limestone particles and the markedly angular, flake-shaped morphology of the ceramic fragments
- The bottom row presents the corresponding ground powders obtained after the ball-milling and sieving procedures described above, both calibrated to an equivalent fineness (≈ 25% retained on the 45 µm sieve).

The morphological contrast observed between the two raw materials is expected to be partly preserved at the powder scale and may influence the rheological behavior of the fresh mixtures.

2.1.4. Chemical and Physical Characteristics

The following table presents the comparative chemical composition of the cements, limestone fillers (LF), and sanitary ceramic fillers (SCF). The data presented in Table 1 highlight significant differences between limestone fillers and sanitary ceramic fillers. The high $CaCO_3$ content and loss on ignition of limestone fillers indicate their mainly inert filler role, contributing primarily to particle packing and workability. In contrast, although the high SiO_2 and Al_2O_3 contents of sanitary ceramic fillers may indicate potential pozzolanic reactivity, these chemical features alone are not sufficient to confirm microstructural densification, which would require direct experimental evidence (e.g., SEM, XRD, MIP, or EDS analysis). These compositional characteristics may nonetheless influence long-term mechanical performance and the quality of the repair interface.

Table 1. Comparative chemical and physical characteristics of the cements, limestone fillers (LF), and sanitary ceramic fillers (SCF)

Component (%)	LF	SCF	CEM I 52.5 N	CEM II/B 42.5 N
SiO_2	2.97	63.56	22.14	21.90
Al_2O_3	0.90	28.66	7.08	6.30
Fe_2O_3	0.95	1.20	3.41	2.50
CaO	—	—	63.72	60.28
MgO	0.28	0.37	0.86	1.70
SO_3	0.06	0.34	1.90	2.50
K_2O	0.10	0.85	0.69	0.20
Na_2O	0.20	1.64	0.17	0.20
P_2O_5	—	0.12	—	—
TiO_2	—	0.37	—	—
Cr_2O_3	0.01	0.01	< 0.0002	0.01
Mn_2O_3	0.01	0.02	—	—
$CaCO_3$	94.50	2.83	—	4.40
Loss on ignition (LOI, %)	43.20	1.46	1.48	4.82
Density (g/cm^3)	2.63	2.53	3.15	3.05
% Retained on 45 µm sieve	27.00	19.00	—	—

2.1.5. Aggregates

Two granular skeletons were used in this study: one for the SCSC repair mixtures and a separate one for the ordinary substrate concrete (OSC) used in the bond tests. Aggregates used in the SCSC mixtures:

- A siliceous fine sand (0/0.63 mm), with a fineness modulus (FM) of 1.2 and a bulk density of 1.45 g/cm^3, incorporated at 600 kg/m^3;
- A quarry sand (0/4 mm), with an FM of 2.8 and a bulk density of 1.65 g/cm^3, incorporated at 500 kg/m^3;
- A 3/5 mm gravel, with a bulk density of 1.60 g/cm^3, incorporated at 400 kg/m^3 in order to provide a slight coarse fraction that improves the granular skeleton compactness and the hardened-state mechanical performance while preserving self-compacting behavior. No coarser gravel (8/15 mm) was used in the SCSC mixtures.

Aggregates used in the ordinary substrate concrete (OSC):

- The same fine sand and quarry sand were used, at reduced dosages (152 and 470 kg/m^3, respectively), combined with the 3/5 mm gravel (327 kg/m^3) and an additional 8/15 mm gravel (bulk density 1.65 g/cm^3, 880 kg/m^3). The 8/15 mm gravel was used exclusively in the OSC and represents a conventional non–self-compacting concrete typical of structural elements that may subsequently require repair.

The combined use of these aggregates allows the development of a well-graded granular skeleton for each of the two concretes, ensuring adequate particle packing and providing mechanical compatibility between the SCSC repair layer and the existing concrete substrate.

2.1.6. Admixture

A polycarboxylate-based superplasticizer (Medaflow 30) with a 30% solid content and a density of 1.08 g/cm^3, conforming to NF EN 934-2 [48], was used to achieve the desired workability. The dosage of the superplasticizer was kept constant for all mixtures in order to isolate the effect of the substitution of limestone fillers by sanitary ceramic fillers on the rheological behavior of SCSC.

2.1.7. Mixing Water

Potable water conforming to NF EN 1008 [49] was used in all mixtures. The mixing water was used at laboratory ambient temperature (approximately 20 ± 2 °C), and no specific pre-treatment was applied.

2.2. Mix Design of Self-Compacting Sand Concrete (SCSC)

Five SCSC formulations were developed by progressively replacing the limestone fillers (LF) with sanitary ceramic fillers (SCF) at substitution ratios of 0%, 25%, 50%, 75%, and 100%. These substitution levels were selected to systematically evaluate the influence of SCF across a wide range of replacement ratios, allowing the identification of possible threshold effects and optimal substitution levels. In addition to these SCSC mixes, a reference ordinary substrate concrete (OSC) was prepared and used as the base material for the adhesion tests. The SCSC mixtures were designated as follows:

C0: 100% LF (0% SCF)
C25: 75% LF – 25% SCF
C50: 50% LF – 50% SCF
C75: 25% LF – 75% SCF
C100: 100% SCF (0% LF).

Table 2. Mix composition of the SCSC repair mixtures (C0–C100) and of the OSC substrate concrete (kg/m^3)

Constituents	C0	C25	C50	C75	C100	OSC
CEM I 52.5 N	400	400	400	400	400	—
CEM II/B 42.5 N	—	—	—	—	—	350
Limestone filler (LF)	160	120	80	40	0	—
Ceramic filler (SCF)	0	40	80	120	160	—
Siliceous fine sand (0/0.63 mm)	600	600	600	600	600	152
Quarry sand 0/4 mm	500	500	500	500	500	470
Gravel 3/5 mm	400	400	400	400	400	327
Granulate 8/15 mm	—	—	—	—	—	880
Water	180	180	180	180	180	210
Superplasticizer	12	12	12	12	12	—
Water-cement ratio	0.45	0.45	0.45	0.45	0.45	0.60

The ordinary substrate concrete (OSC) mix was produced following a conventional formulation commonly used for structural concrete, and it served as the receiving concrete surface for the repair bond tests. The mix-design parameters were selected following a controlled-comparison approach, in which only the LF→SCF substitution ratio was varied from one mixture to another, while all other parameters were kept strictly constant. The rationale supporting each parameter is summarized below:

- Constant binder content (cement + filler = 560 kg/m^3): this value corresponds to standard practice for SCSC formulations and ensures the high paste volume needed to maintain self-compacting behavior;
- Constant W/C ratio (0.45): selected on the basis of preliminary tests and consistent with the early-age strength requirements of structural repair materials;
- Constant superplasticizer dosage (12 kg/m^3): kept identical for all five SCSC mixtures so that any observed change in rheology or mechanical performance can be attributed solely to the LF→SCF substitution and not to admixture adjustments;
- Constant aggregate skeleton (siliceous fine sand 600 kg/m^3, quarry sand 500 kg/m^3, 3/5 mm gravel 400 kg/m^3): a fixed granular composition was maintained to remove any granulometric bias from the comparison between mixtures;
- Constant total filler content (160 kg/m^3): progressively shifted from 100% LF to 100% SCF in 25% increments, allowing the systematic identification of possible threshold effects across the full substitution range.

This approach ensures that the variations observed across mixtures C0 to C100 can be unambiguously attributed to the chemical and morphological nature of the filler. The detailed mix proportions of all SCSC formulations (C0 to C100), as well as the ordinary substrate concrete (OSC), are summarized in Table 2.

2.3. Testing Methods

2.3.1. Fresh-State Characterization:

2.3.1.1 Mini-Slump Flow Test

The mini-slump flow test was carried out using a reduced-size truncated cone mold (height: 150 mm, bottom diameter: 100 mm, top diameter: 50 mm) (Figure 2), following the European recommendations for self-compacting concretes [45], adapted in this study to the specific case of self-compacting sand concretes (SCSC). Preliminary trial tests were conducted to verify the suitability of this adapted procedure for mixtures incorporating sanitary ceramic fillers. The cone was filled in a single lift without compaction, leveled at the top, and then vertically lifted to allow the mixture to flow freely under its own weight. The average spread diameter was determined by measuring the flow in two perpendicular directions and calculating their mean value. This test provides a direct indication of the mixture's filling ability and flowability at the fresh state. A higher spread diameter reflects improved deformability and lower yield stress, whereas a lower spread indicates reduced workability.

Unlike conventional self-compacting concretes, for which the EFNARC guidelines define a typical slump-flow window of 60–75 cm using the Abrams cone, no fully standardized acceptance limits exist for the mini-slump flow test applied to self-compacting sand concretes (SCSC). In the present study, the EFNARC-based criterion was therefore adapted to the SCSC context, where the lower paste volume and the absence of coarse aggregates lead to systematically smaller spread values. Based on values commonly reported in the literature for SCSC, an adapted workability window of 22–28 cm was adopted as a reasonable acceptance criterion, combined with a V-funnel flow time below 15 s, ensuring proper self-compacting behavior without segregation. All five mixtures investigated in this study fall within this adapted SCSC workability window (see Section 3.1), confirming that the selected mixture design ensured adequate self-compacting behavior with a constant superplasticizer dosage.

2.3.1.2 Mini V-funnel test:

The mini-V-funnel test was performed to assess the viscosity and flow resistance of the SCSC mixtures in accordance with an adapted version of the EFNARC procedure [45]. The apparatus consists of a small V-shaped funnel equipped with a bottom discharge gate. Prior to each test, the interior surfaces of the funnel were moistened to minimize friction. The mixture was then poured into the funnel without compaction until completely full, and the bottom gate was opened to allow the material to flow out freely.

Fig. 2. Slump flow test using the mini-cone

Fig. 3. Flow time test using the V-funnel

The flow time, measured from the moment the gate is opened until the first visible break in the outflow stream, represents the mixture's viscosity and resistance to deformation. Shorter flow times indicate lower viscosity and better fluidity, whereas longer times reflect increased internal friction and reduced flowability. Each rheological test was performed three times for each mixture, and the reported values correspond to the average of the three measurements in order to ensure the repeatability and reliability of the results.

2.3.2. Hardened-State Characterization

2.3.2.1. Mechanical Properties

- Flexural strength: Measured on 40 × 40 × 160 mm prismatic specimens using a three-point bending test according to NF EN 196-1 [46] at 7, 28, 90, and 180 days. For each mixture and curing age, three specimens were tested and the reported values correspond to the average results.
- Compressive strength: Determined on the halves of the prisms obtained from the flexural tests, in accordance with NF EN 196-1 [46], at the same curing ages. The compressive strength results correspond to the mean value obtained from six half-prisms.

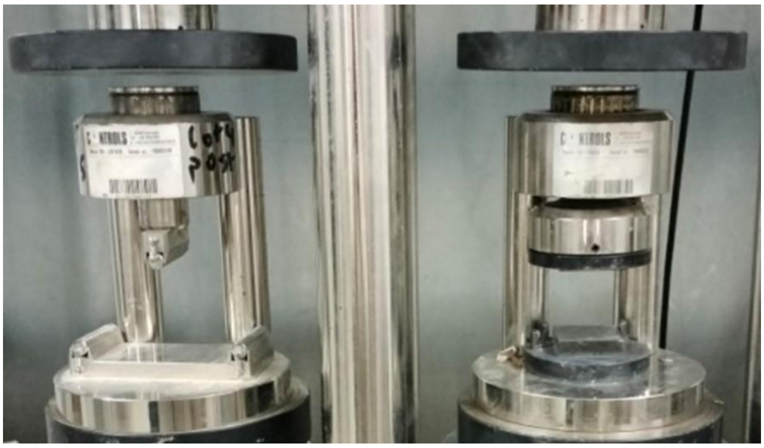

Fig. 4. Mechanical strength testing on prismatic specimens (4×4×16 cm^3)

2.3.2.2. Bond Strength (Pull-off Test)

The bond strength between the repair material and the substrate was measured by direct tension (pull-off) following ASTM C1583 [37,39]. Steel disks (50 mm in diameter) were glued to the surface of the repaired SCSC layer after 90 days of curing. A perpendicular tensile load was applied using a dynamometer until failure. Failure modes were visually identified after testing in accordance with ASTM C1583 recommendations. The bond strength and failure mode were recorded as follows:

- Failure in the substrate,
- At the interface,
- Within the repair layer, or
- At the disk–adhesive joint.

Three tests were conducted for each formulation. For the bond tests, ordinary concrete slabs (C25/30) measuring 300 × 300 × 50 mm were prepared and cured for at least 90 days. Their surfaces were sandblasted to obtain a uniform and controlled roughness before applying a 30 mm thick SCSC repair layer.

Fig. 5. Apparatus used to evaluate the bond strength between the concrete substrate and the SCSC repair layer

3. Results and Discussion

3.1. Fresh-State Parameters

The fresh-state properties of self-compacting sand concretes (SCSC) are of fundamental importance for their practical use especially in structural repair applications where the mixture must flow easily and fill complex or restricted geometries without segregation. Figure 6 illustrates the results of the mini-slump flow and V-funnel flow time tests for the various substitution ratios investigated. Each test was repeated three times for every mixture, and the presented values correspond to the average results, with standard deviation considered to evaluate measurement variability.

The results clearly show that the progressive replacement of limestone fillers (LF) with sanitary ceramic fillers (SCF) leads to a reduction in flowability and an increase in viscosity of the SCSC mixtures. This trend reflects the higher angularity and rougher surface texture of ceramic particles, which increase interparticle friction and hinder the flow of the fresh mixture. The mini-slump flow diameter decreased from 26.5 cm (C0) to 22.8 cm (C100). A reduction of approximately 14%, while the V-funnel flow time increased from 7.2 s to 12.5 s (a 74% increase). These observations are consistent with the findings of Subaşı et al. [15], who reported a 10–15% decrease in slump flow and a significant increase in flow time when ceramic powders were used in self-compacting concrete, due to similar morphological characteristics.

Likewise, Zimbili et al. [16] observed an increased demand for superplasticizer when ceramic fillers replaced limestone fillers in mortars. However, the reduction in flowability observed in the present study was not strictly linear; a more pronounced drop was recorded between 25% and 50% SCF, suggesting stronger interactions between ceramic filler particles and the superplasticizer molecules. In addition, the higher angularity and surface roughness of ceramic fillers may increase particle interlocking and internal friction within the fresh mixture. Their slightly higher water absorption capacity may also reduce the amount of free water available for lubrication, leading to a more pronounced reduction in flowability at intermediate substitution levels, an effect also reported by Restuccia and Ferro [11]. Despite this reduction, all five mixtures — including the 100% SCF formulation — remained within the adapted SCSC workability window defined in Section 2.3.1 (slump flow between 22 cm and 28 cm; V-funnel time below 15 s), with a constant superplasticizer dosage of 12 kg/m^3. This confirms that the complete replacement of LF by SCF remains technically feasible for self-compacting sand concretes intended for structural repair, without any adjustment of the admixture dosage. The findings extend those of Medina et al. [10] and Subaşı et al. [15], by providing new experimental evidence on the effect of high substitution levels (up to 100%) in the specific context of structural repair applications.

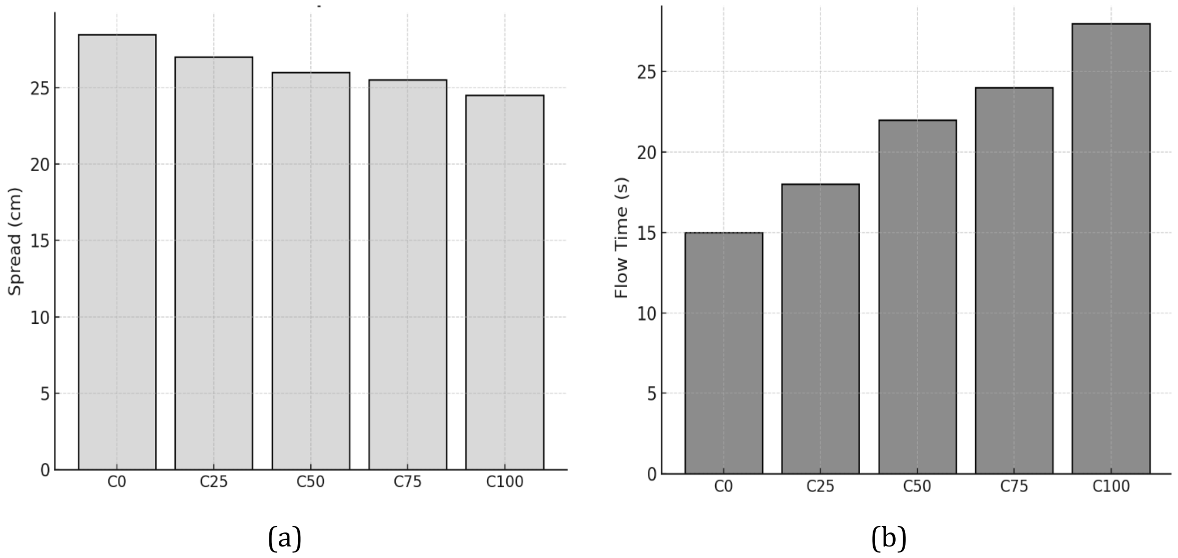

Fig. 6. Rheological properties of SCSC as a function of the substitution rate of sanitary ceramic fillers: (a) Mini-cone spread; (b) V-funnel flow time

3.2. Mechanical Properties in the Hardened State

3.2.1. Compressive Strength

For each mixture and curing age, three prismatic specimens were tested in flexure and the compressive strength was determined on the six resulting half-prisms. The reported values correspond to the average compressive strength. The evolution of compressive strength for the different SCSC formulations as a function of curing time is presented in Figure 7.

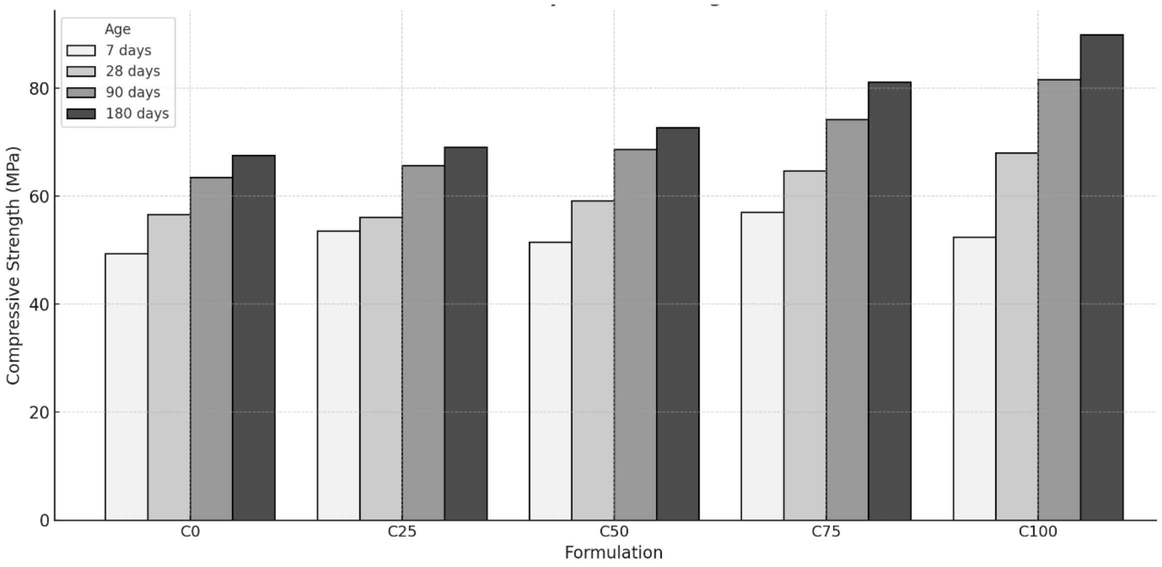

Fig. 7. Evolution of compressive strength of SCSC with time and substitution rate of sanitary ceramic fillers

The results indicate that the progressive substitution of limestone fillers (LF) with sanitary ceramic fillers (SCF) significantly enhances the mechanical performance of SCSC, particularly at medium and long curing ages. At 28 days, the compressive strength increased from 56.5 MPa (C0) to 68.2 MPa (C100), corresponding to an improvement of +21%. At 180 days, the strength rose from 61.8 MPa to 78.5 MPa, an increase of +27% compared with the reference mixture. This improvement is consistent with several mechanisms commonly proposed in the literature for ceramic powders in cementitious systems. In the absence of dedicated microstructural characterization in the present study (such as SEM, XRD, or MIP analyses), these mechanisms are introduced here as plausible contributing factors rather than as directly demonstrated effects:

- Possible pozzolanic reactivity — The high silica and alumina contents of SCF may favor the formation of additional C–S–H gel, which could potentially contribute to matrix densification at medium and long curing ages [10,12,15]. However, this mechanism remains inferential in the absence of direct microstructural validation (e.g., SEM, XRD, MIP, or EDS analysis).
- Filler effect — The fine SCF particles are likely to fill voids within the cementitious matrix, potentially improving packing density and reducing porosity.
- Mechanical interlocking — The angular particle morphology of SCF may enhance particle–matrix interaction, possibly contributing to the overall mechanical performance.

The progressive strength gains observed up to 180 days are compatible with the slow, time-dependent nature of pozzolanic reactions reported for ceramic powders [10,15], although direct microstructural evidence would be required to confirm the relative contribution of each mechanism in the specific case of the SCSC formulations investigated here. These findings are consistent with those reported by Medina et al. [23], who observed strength gains in concretes containing reactive ceramic powders. Similarly, Pacheco-Torgal and Jalali [12] and Subaşı et al. [15] demonstrated that fine ceramic powders could densify the cement matrix and improve mechanical strength. However, these results contrast with studies such as [31,32], which reported a strength decrease when coarse ceramic waste was used. This difference highlights the importance of particle fineness (3800 cm^2/g) and optimized superplasticizer dosage in maintaining a favorable effective water-to-cement ratio.

3.2.2. Flexural Strength

Figure 8 illustrates the development of flexural strength over time for all formulations. The trend in flexural strength mirrors that observed in compression, with even more pronounced gains. At 28 days, the flexural strength increased from 9.5 MPa (C0) to 11.8 MPa (C100), representing an improvement of +24.2%. At 180 days, it reached 13.2 MPa, corresponding to a total increase of +32% relative to the reference mixture.

The greater relative improvement observed in flexural strength compared with compressive strength may be indicative of an enhanced interfacial transition zone (ITZ) between the cement paste and the fine aggregates, although this interpretation remains inferential in the absence of direct microstructural observation. The angular morphology of SCF particles could contribute to a stronger mechanical anchorage at the paste–aggregate interface, while possible localized pozzolanic reactions associated with the silico-aluminous nature of SCF may also play a role within this critical zone. These tentative interpretations are consistent with the macroscopic observations reported by Courard et al. [17] and Hossain and Lachemi [30], who linked the addition of fine, reactive particles to a reinforcement of the ITZ and a reduction of crack propagation; however, direct microstructural characterization (e.g., SEM, EDS, MIP) would be required to confirm these mechanisms in the specific case of SCSC incorporating sanitary ceramic fillers.

The flexural-to-compressive strength ratio (Rf/Rc) increased from 0.168 (C0) to 0.173 (C100) at 28 days, reflecting a modest but meaningful improvement in tensile–flexural performance. This interpretation is consistent with the mechanical results obtained in the present study and could be tentatively associated with a possible densification and homogenization of the microstructure; however, it should be regarded as an inferential interpretation rather than as direct evidence, since no direct microstructural characterization (e.g., SEM, XRD, MIP, EDS) was performed in this study. In summary, the complete replacement of limestone fillers with sanitary ceramic fillers yields mechanical benefits rather than performance loss. This finding contrasts with several earlier studies on coarser ceramic wastes and demonstrates that fine SCF incorporation is a technically viable and sustainable option for producing high-performance SCSC repair materials.

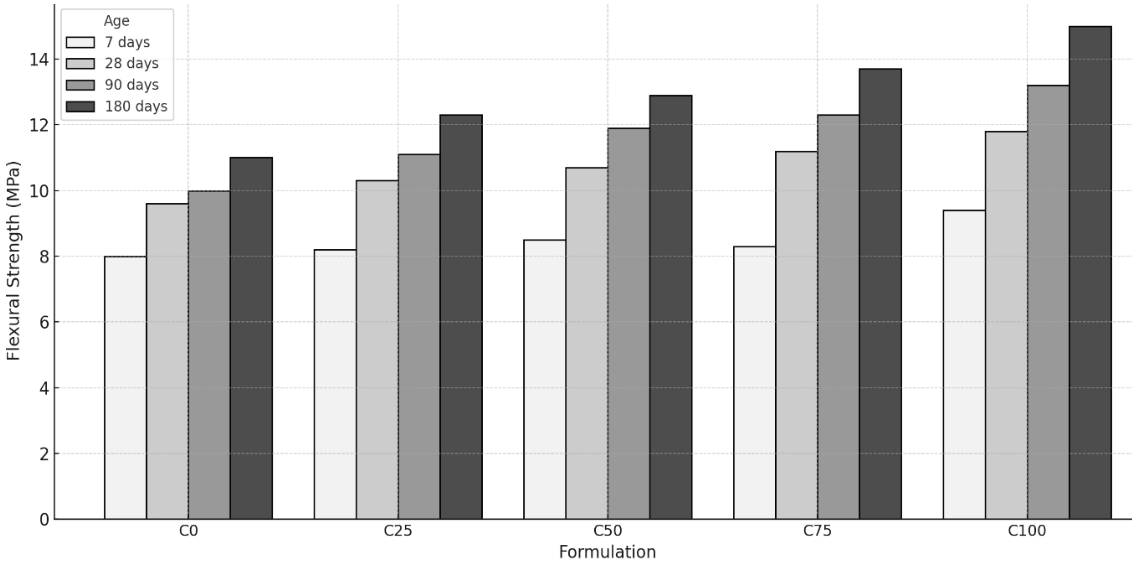

Fig. 8. Evolution of flexural strength of SCSC with time and substitution rate of sanitary ceramic fillers

3.3. Bond Strength (Adhesion to Substrate)

The bond between the repair material and the existing substrate is a critical factor governing the durability and effectiveness of structural repairs. Figure 9 presents the results of direct tensile bond strength (pull-off) tests performed at 90 days for the various SCSC formulations. All mixtures exhibited satisfactory adhesion performance, both in terms of bond strength and failure mode. The variation of bond strength with increasing substitution of sanitary ceramic fillers (SCF) showed a non-monotonic evolution, neither purely increasing nor decreasing.

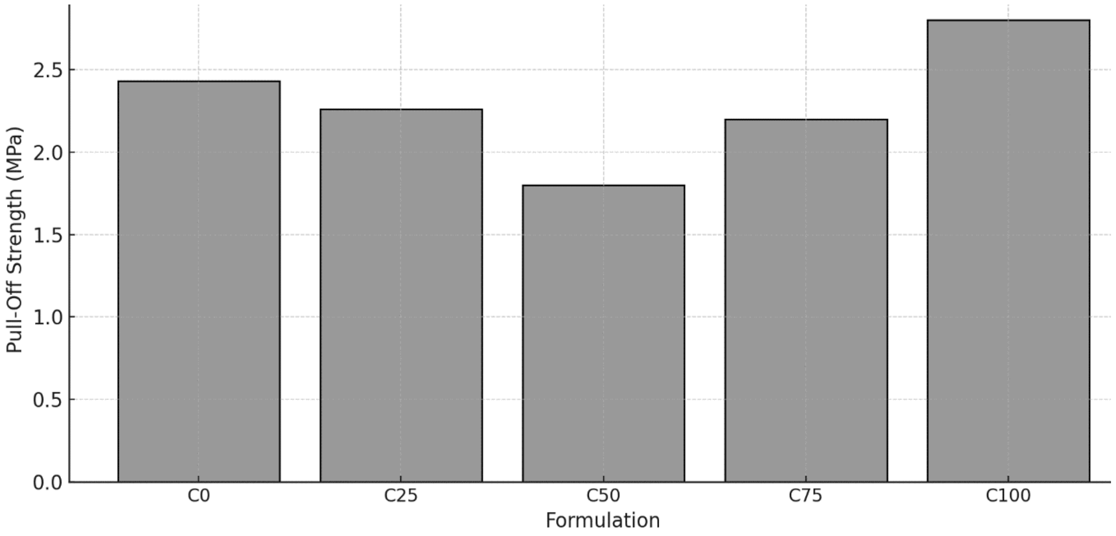

Fig. 9. Pull-off bond strength of SCSC as a function of the substitution rate of sanitary ceramic fillers

The reference mixture (C0) achieved a bond strength of approximately 2.4 MPa, which slightly decreased to 2.2 MPa for C25. A more pronounced reduction was observed for the C50 formulation, reaching approximately 1.8 MPa. However, the bond strength increased again at higher substitution levels, reaching approximately 2.2 MPa for C75 and the highest value of 2.8 MPa for C100, corresponding to an improvement of approximately +17% compared with the reference mixture C0 (2.4 MPa). The C100 formulation therefore exhibits the best bond performance among all investigated mixtures, in agreement with its highest mechanical performance reported in

Sections 3.2.1 and 3.2.2, and is consequently identified as the optimal formulation of this study (in line with the Abstract and the Conclusion).

This temporary decrease at 50% SCF may be attributed to microstructural adjustments occurring at intermediate substitution levels. At this stage, the coexistence of limestone and ceramic fillers with different particle morphologies and surface textures may temporarily reduce packing efficiency and stress transfer at the repair–substrate interface. These results, combined with the failure patterns observed in the substrate, indicate that all studied formulations provided adequate adhesion. They further support the observation that the complete substitution of limestone fillers by sanitary ceramic fillers does not compromise bond performance [40]. The good adhesion observed (in terms of both bond strength and failure location) may be attributed to several synergistic factors:

3.3.1 Enhanced mechanical interlocking

The angular particle morphology of SCF may promote a stronger mechanical bond at the interface with the roughened substrate surface, a mechanism consistent with the improved anchorage commonly reported in the literature [33, 34, 36]. This effect appears to become more pronounced as the SCF content increases, although direct microstructural confirmation would be required to validate this interpretation.

3.3.2 Physicochemical interactions

The silico-aluminous nature of SCF could also influence the interfacial chemistry. In particular, possible localized pozzolanic reactions associated with the high silica and alumina contents may contribute to an improved compatibility at the repair–substrate interface [35], although these interpretations remain inferential and would require direct microstructural confirmation (e.g., SEM/EDS investigation of the interfacial transition zone). The analysis of failure modes during the pull-off tests provides complementary insights into the quality of adhesion (see Figure 10). As illustrated in Figure 10, the repaired specimen clearly shows the repair material, the interface region, and the concrete substrate, allowing the identification of the failure location after the pull-off test. For the formulations C0 and C25, failure occurred partially cohesively, with fragments of substrate adhering to the repair layer, indicating good but not optimal bond strength.

Fig. 10. Failure modes of SCSC-repaired specimens

For higher substitution levels (≥50% SCF), failure predominantly occurred within the concrete substrate, indicating that the bond strength exceeded the tensile strength of the substrate and that the interface was no longer the weakest zone of the system. This evolution in failure modes suggests an improvement in interfacial quality with increasing SCF content and may be regarded as supporting evidence of enhanced bond performance, although a definitive confirmation would require direct microstructural characterization (e.g., SEM/EDS investigation of the interfacial transition zone).

Although the overall pull-off strength did not increase monotonically, the highest bond performance was clearly obtained for the C100 formulation, which combines the maximum pull-off strength (2.8 MPa) with a failure mode predominantly located within the substrate. Taken together, these observations suggest that higher SCF contents — and specifically the C100 mixture may contribute to a more robust repair–substrate interface. In the context of practical repair applications, this finding is particularly advantageous, as it suggests improved long-term adhesion and durability of SCSC repair layers [38], and further supports the identification of C100 as the optimal formulation of this study.

4. Conclusion

This study investigated the influence of progressively replacing limestone fillers (LF) by sanitary ceramic fillers (SCF) — at substitution ratios of 0%, 25%, 50%, 75%, and 100% — on the fresh-state, mechanical, and bond properties of self-compacting sand concrete (SCSC) designed for structural repair applications. A controlled-comparison approach was adopted, in which the binder content, water-to-cement ratio, superplasticizer dosage (kept strictly constant at 12 kg/m^3), and aggregate skeleton were maintained constant from one mixture to another, so that any observed variation could be attributed unambiguously to the LF→SCF substitution.

In the fresh state, increasing the SCF content led to a progressive reduction in flowability (mini-slump from 26.5 to 22.8 cm) and an increase in viscosity (V-funnel from 7.2 to 12.5 s), which can be related to the angular morphology and rougher surface texture of ceramic particles. Nevertheless, all five mixtures — including C100 — remained within the adapted SCSC workability window (22–28 cm; V-funnel < 15 s) without any adjustment of the superplasticizer dosage, confirming the technical feasibility of the full LF→SCF substitution.

In the hardened state, replacing LF by SCF led to clear gains in compressive and flexural strengths, especially at medium and long curing ages. At 28 days, the C100 mixture achieved approximately +21% in compressive strength and +24% in flexural strength compared with the reference C0. These improvements are consistent with mechanisms commonly proposed in the literature for fine ceramic powders — namely possible pozzolanic reactivity, an effective filler effect, and enhanced mechanical interlocking — although direct microstructural evidence (e.g., SEM, XRD, MIP) would be required to confirm their respective contributions. Regarding bond performance, the pull-off tests revealed a non-monotonic evolution with substitution ratio (1.8 MPa at C50, 2.4 MPa at C0), with the highest value of 2.8 MPa obtained for C100, corresponding to a +17% improvement over the reference.

The failure mode analysis confirmed that, for substitution levels ≥ 50%, failure predominantly occurred within the substrate, indicating that the repair–substrate interface was no longer the weakest zone of the system. Taken together, the C100 formulation combines the best compressive strength, the best flexural strength, and the best bond strength among the investigated mixtures, and is therefore identified as the most favorable substitution level of this study, in full agreement with the Abstract. Beyond technical performance, these results suggest that sanitary ceramic waste can be effectively valorized as a sustainable alternative filler for SCSC repair materials, contributing to circular-economy principles by reducing the consumption of natural limestone resources and the environmental impact associated with conventional mineral filler extraction.

The present work was conducted under controlled laboratory conditions and focused on the fresh state, mechanical performance, and bond behavior. Further research should investigate the long-term durability of SCSC incorporating sanitary ceramic fillers under aggressive environmental conditions (chloride exposure, sulfate attack, freeze–thaw cycles), perform microstructural characterization (SEM, XRD, MIP) to directly validate the mechanisms proposed here, and assess their performance in large-scale structural repair applications.

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