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New mix design for 3D printed mortar incorporating recycled fine aggregate

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Abstract

3D printing for construction is an emerging technology with significant potential to replace conventional formwork-based methods. However, printable mortars remain unsustainable due to the high consumption of cement and natural sand. This study addresses this limitation by developing a novel mix design that simultaneously incorporates recycled sand (RS) to reduce natural sand consumption and recycled concrete crushed fines (RCCF) as a partial cement substitutions, establishing a dual-benefit approach for sustainable 3D printing. The experimental procedure began with preliminary printability and strength assessments, followed by rheological investigations and 3D printing trials once performance was confirmed. The results indicate that replacing up to 75% of natural sand with RS and 10% of cement with RCCF significantly minimizes the environmental footprint of the mortar without compromising its fresh or hardened properties. Specifically, the incorporation of RS primarily influences compressive strength while maintaining excellent extrudability, whereas the addition of RCCF has a minor effect on strength while leaving the rheological properties virtually unaffected. By optimizing this simultaneous replacement, the mixture maintained highly satisfactory fresh performance. The optimized mix achieved a spread diameter of 17 cm, yield stress of 157.77 to 160.62 Pa, viscosity of 25.58 to 26.94 Pa-s, and compressive strength between 47.99 and 50 MPa. This study provides a distinct scientific contribution by demonstrating the synergistic viability of dual recycled components, offering a practical approach for developing eco-friendly 3D printing mortars.

Keywords 3D printing concrete (3DPC), Recycled sand, Recycled concrete crushed fines (RCCF), Cement substitution, Rheological behavior, Mix design optimization

1 Introduction

The global population is growing at an unprecedented rate. Given the current global population of approximately 8.2 billion, there is a growing and urgent demand for innovative housing solutions. Typically, it takes from 6 to 12 months to complete the construction of a house, depending on its complexity [1]. Such a pace of construction appears insufficient to keep up with the rapid growth of the global population [2]. In response, the application of 3D printing technology in construction has emerged as a promising and transformative approach [3]. Notably, 3D-printed concrete has gained



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considerable attention as a novel research direction worldwide, with a growing body of studies dedicated to exploring its potential and optimization.

3D concrete printing uses a mortar mixture similar to traditional construction but must meet more stringent performance criteria [4, 5]. Unlike conventional methods, this additive manufacturing process employs a high-capacity pump and printer to deposit material layer by layer [6, 7]. To ensure efficient flow through pipes and successful extrusion, the mixture requires high extrudability, pumpability, and buildability [8–10]. Therefore, mastering rheological properties is essential for developing effective 3D printing mix designs.

Mandal et al. [11] identified the Bingham and Herschel–Bulkley (H-B) models as the most recognized for evaluating cementitious material rheology. While the Bingham model is simple, it cannot describe shear thickening or thinning [12–14]. The H-B model addresses this but is less effective for highly flowable materials like SCC, where the Rousel model is preferred [15, 16]. Other specialized options include the Vom Berg [17] and Robertson–Stiff [18] models. Despite these alternatives, the Bingham model remains the most widely used for 3D printed concrete, as supported by Rehman et al. [19–23].

Early pioneering work by Le et al. [24] demonstrated the baseline feasibility of 3D concrete printing by utilizing Portland cement, fly ash, and silica fume to fulfill fundamental criteria for extrudability and buildability. However, subsequent research quickly transitioned from standard formulations to advanced material tailoring. Notably, Zhang et al. [25] opened a new research framework by incorporating sophisticated additives such as nano-clay. This marked a pivotal shift toward utilizing specialized modifiers to precisely control rheological properties, enhance hardened mechanical strength, and mitigate shrinkage through the filler effect. Moving beyond traditional Portland cement, Chen et al. [26] introduced alternative binder systems, specifically calcium sulfoaluminate cement and metakaolin, to eliminate bleeding between printed layers, guarantee smooth filament extrusion, and minimize the ultimate shrinkage of the printed elements. These foundational investigations reveal that while 3D printable mixtures can be successfully formulated using conventional raw materials, satisfying the strict and often competing demands for tailored rheology, mechanical performance, and post-printing structural stability ultimately necessitates the strategic integration of advanced constituents such as nanomaterials and alternative cementitious binders.

Recent studies highlight the benefits of using mineral additives like fly ash (FA), silica fume (SF), or limestone calcined clay cement (LC3) as eco-friendly cement substitutions to enhance 3D printability. Because these reactive materials possess contrasting mechanisms—where SF increases yield stress and viscosity to reduce setting time and bleeding [27–31], while FA produces a fluidizing effect—combining them has emerged as a strategic formulation approach. For instance, Panda and Tan [32] successfully balanced these competing properties using a binder with 77.5% FA and 2.5% SF, while others utilized SF as an internal lubricant to improve pumping efficiency [33–35]. Parallel to these reactive binders, non-reactive materials like nanoclay (NC) and limestone powder are increasingly deployed to complete the granular skeleton through physical packing rather than C–S–H gel formation. By optimizing particle physics, these inert additives enhance fresh mixture stiffness [36, 37], allowing for a reduced cement content without compromising compressive strength. Specifically, NC directly elevates yield stress and plastic

viscosity [38–43]; although this can hinder pumpability, it remains crucial for ensuring that freshly deposited layers retain their shape and resist structural collapse.

Toward the development of environmentally friendly concrete mixtures, many recent studies have focused on replacing Portland cement with alternative binder systems, such as alkali-activated materials, geopolymers [44], and supplementary cementitious materials (SCMs) [45], to reduce CO₂ emissions. Additionally, the use of recycled aggregates and waste materials, such as recycled sand [46], mine tailings, waste tire rubber powder, and recycled glass, has also been proven to be an effective solution for reducing the extraction of natural resources and enhancing the sustainability of construction materials [47].

However, most current research only evaluates the individual effects of each alternative material. In particular, the simultaneous impact of recycled fine aggregate and RCCF within the same mix design has not yet been systematically investigated. Therefore, this study is conducted, building upon the findings of previous research, to clarify the combined effects of these two materials on the properties of both the fresh mixture and the hardened material.

To reduce the consumption of natural aggregates, RS is investigated in this study as a direct replacement for natural river sand. Although RS generally possesses lower specific gravity and higher water absorption compared to its natural counterpart, it can satisfy the stringent requirements of 3D printing. Studies show that 100% RS substitution can improve buildability, though it may reduce open time and extrudability [48]. Similarly, replacing river sand with recycled glass maintains comparable viscosity but can significantly reduce compressive strength [49]. While RS mixtures often achieve only 60–70% of the strength of natural sand counterparts, these limitations can be mitigated by incorporating fibers, mineral additives, or by washing the recycled sand prior to use [50–53]. Overall, while challenges in workability and mechanical properties remain, the strategic use of admixtures ensures these sustainable mixtures meet the key technical standards for 3D printing.

In addition to aggregate replacement, this study investigates the potential of RCCF, an ultra-fine fraction ($< 63 \mu\text{m}$) generated during recycled aggregate production, as a partial cement substitution in 3D printable concrete. Owing to its fine particle size, RCCF is expected to contribute to strength development primarily through a physical filler effect, densifying particle packing within the matrix; any residual pozzolanic reactivity remains unverified and is treated in this study as a hypothesis rather than an established mechanism. Although a few studies have examined RCCF as a supplementary cementitious material in conventional cementitious composites, its application in extrusion-based 3D concrete printing remains largely unexplored.

Previous studies have shown that RCCF can replace up to 25% of cement in conventional cementitious materials without significantly affecting mechanical properties. However, these studies were limited to conventional cementitious material and did not extend to 3D printable concrete, where rheological and buildability requirements are fundamentally different [54].

In 3D concrete printing, research [55] has mainly focused on recycled fine aggregates (up to $\sim 2 \text{ mm}$) or mixed recycled powders from construction and demolition waste, rather than ultra-fine fractions such as RCCF ($< 63 \mu\text{m}$), which play a distinct role in particle packing and rheology. Robayo-Salazar et al. [56] investigated mixed recycled

powders ($< 75 \mu\text{m}$) and recycled fine aggregates in 3D printable mixtures, while Cavalcante et al. [57] studied recycled concrete powder in low-cement printable pastes, showing promising results up to 50% cement replacement. However, since these studies did not isolate the effect of RCCF as a distinct material generated directly from recycled aggregate production, its influence on the rheology, printability, and hardened performance of 3D printable concrete remains insufficiently understood.

This lack of targeted investigation forms the basis of the present study, which focuses on evaluating RCCF as a cement substitution. Addressing this knowledge gap is particularly important because the performance of printable cementitious materials is highly sensitive to particle size distribution and rheological properties. Furthermore, utilizing RCCF in bound cementitious systems provides a sustainable route for valorizing an abundant waste stream, reducing cement consumption, and mitigating potential environmental and health concerns associated with the disposal of ultra-fine recycled concrete particles.

Therefore, this study aims to develop a *New Mix Design for 3D Printed Mortar Incorporating Recycled Fine Aggregate*. The objectives of this research are to: (i) evaluate the influence of RCCF and RS on the rheological properties of the mixture; (ii) assess their effects on printability, particularly in terms of extrudability and buildability; and (iii) investigate their contribution to mechanical performance and potential for reducing cement consumption. Through this approach, the study seeks to provide a sustainable and technically viable pathway for valorizing ultra-fine construction waste in 3D concrete printing applications.

2 Materials and methods

2.1 Materials

CEM III A 52.5 N cement was used in this study as the main binder. This eco-friendly cement was chosen over traditional Ordinary Portland Cement to align the research with sustainable development goals. By replacing clinker with blast furnace slag, CEM III A substantially reduces the carbon footprint, reflecting the current industrial shift toward green and sustainable construction.

Two types of sand were used: one was natural sand with a particle size smaller than 2 mm, and the other was recycled sand, also used at a fine particle size of 0–2 mm. The natural sand is river sand, and the recycled sand, supplied by SATEA (TRBA Group, Belgium), is derived from construction and demolition waste. It is sourced from infrastructure projects and refined into high-quality aggregates for sustainable applications. Their characteristics are shown in Table 1 and the particle size distribution is shown in the Fig. 1. The water absorption test of the sand was performed in accordance with the EN 1097-6 standard. To ensure consistency, the water absorption property of the sand was maintained stable throughout the entire study. The water absorption of recycled sand is significantly higher than that of natural sand due to its much higher concentration of fine particles – as presented in Fig. 1.

Table 1 Physical properties of fine aggregates

Fine Aggregate	Density (kg/m^3)	Maximum particle size (mm)	Water absorption(%)
Natural sand	2650	2	0.18
Recycled sand	2400	2	14.0

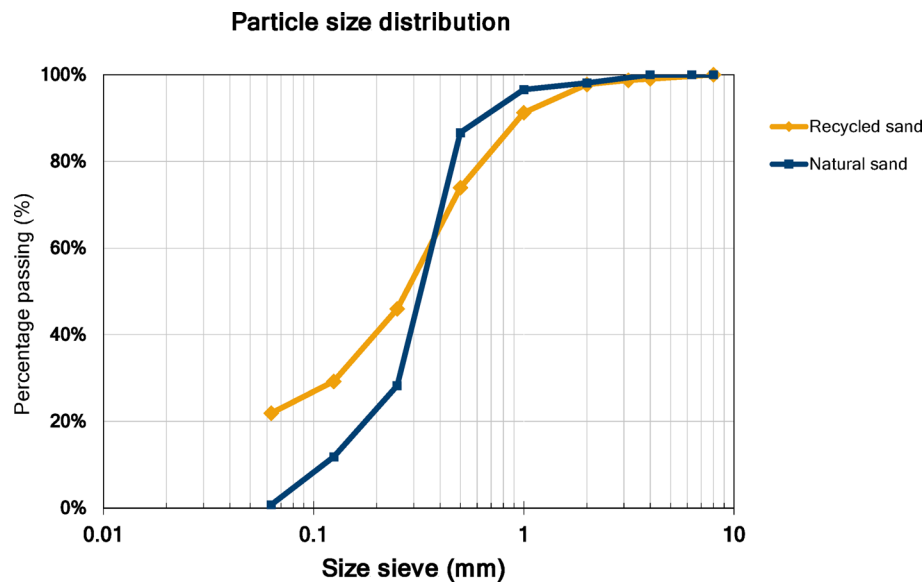


Fig. 1 Particle size distribution of sands

Table 2 Mineral composition of the RCCF

Mineral	Percentage (%)
Quartz — SiO_2	60.53
Muscovite (2M1) — $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	11.80
Albite — $\text{NaAlSi}_3\text{O}_8$	8.47
Orthoclase — KAlSi_3O_8	4.84
Calcite — CaCO_3	9.34
Chlorite IIb	5.02

In addition, to partially replace cement in the study, RCCF was also used. The main composition of RCCF is shown in Table 2, and RCCF has a particle size range of 0–63 micrometers and have the density of 2400 kg/m^3 . The particle size distributions of the two RCCF samples, together with the main physical properties and characteristics of RCCF, as measured using a Mastersizer 2000, are presented in Fig. 2; Table 3.

The superplasticizer used was Sika Betonverflüssiger BV 3 M, which has been shown to be particularly effective in reducing friction forces between cement and aggregates, resulting in more homogeneous concrete with a lower tendency for segregation, and is recommended for use in pumped concrete.

2.2 Experimental methods

2.2.1 Mixing preparation

The mixing procedure for the 3D printing mortar does not require any special processing conditions; therefore, it is similar to the conventional mixing procedure used for ordinary concrete mixtures.

For laboratory-scale mixture preparation, a small mixer with a capacity of 3 L was used. When a larger volume of material was required for 3D printing, a mixer with a capacity of 35 L was employed (Fig. 3). The mixing procedure was carried out as follows:

- Step 1: Add water and cement, then mix for 30 s.
- Step 2: Gradually introduce sand while mixing for 30 s.

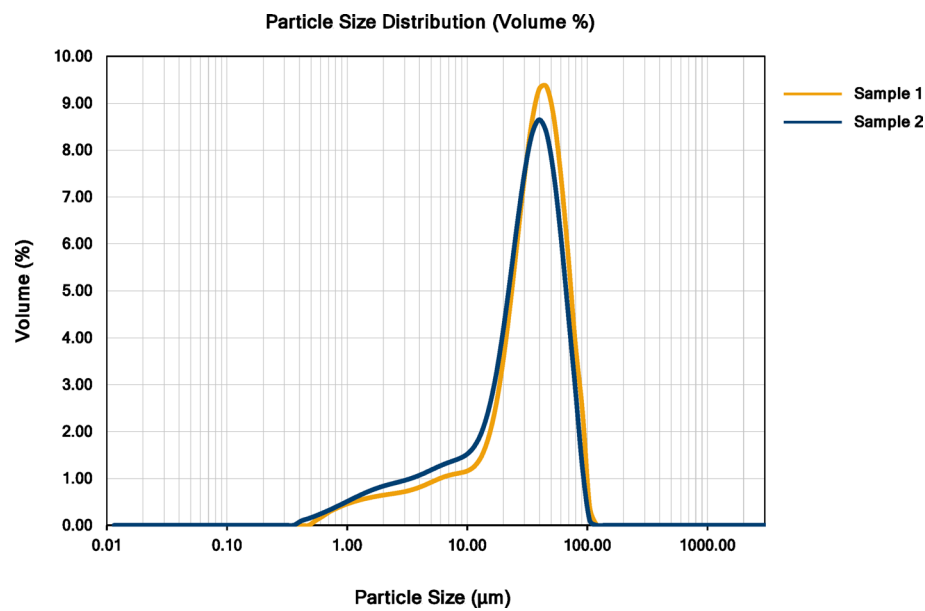


Fig. 2 Particle size distribution curves of RCCF samples measured via laser diffraction

Table 3 Main physical parameters and characteristic particle sizes of RCCF

Parameter	Unit	Sample 1	Sample 2	Average
Specific surface area	m ² /g	0.696	0.555	0.626
Surface weighted mean D[3,2]	μm	8.615	10.805	9.710
Volume weighted mean D[4,3]	μm	30.572	34.650	32.611
Cumulative percentile d(0.1)	μm	3.720	5.298	4.509
Cumulative percentile d(0.5)	μm	29.057	33.251	31.154
Cumulative percentile d(0.9)	μm	58.439	63.592	61.016

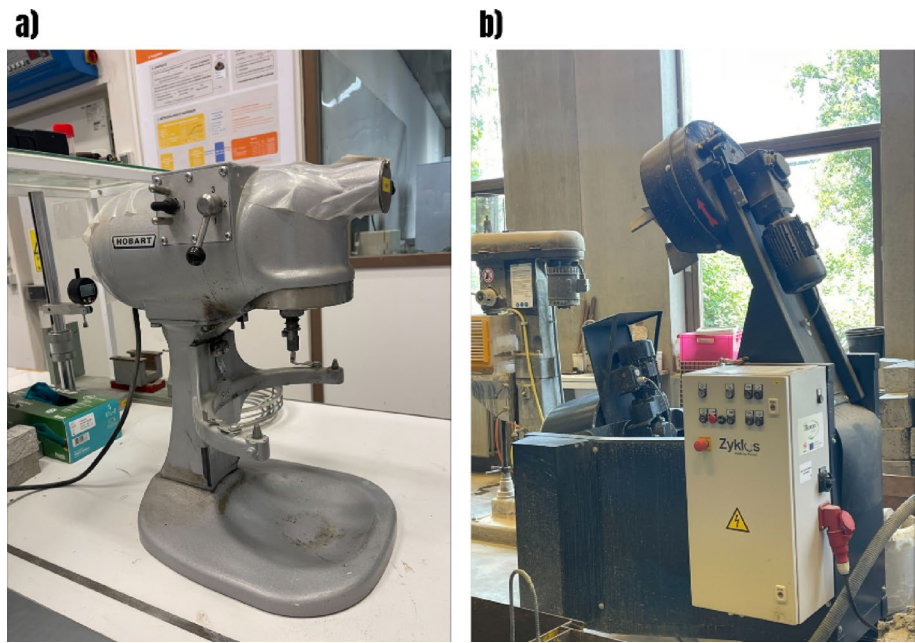


Fig. 3 Mixing equipment used in this study: (a) 3 L mixer; (b) 35 L mixer

- Step 3: Mix for 30 s. (total time: 1 min 30 s)
- Step 4: Stop the mixer for 1 min 30 s. During the first 30 s of this pause, use a rubber scraper to remove all mortar adhering to the walls and bottom of the mixing bowl.
- Step 5: Resume mixing for 1 min and add superplasticizer (if necessary).

To account for the significant difference in water absorption between the recycled sand (14%) and natural sand (0.18%), an additional amount of water equivalent to the absorption differential was calculated and added during the mixing process. This compensation ensures that the effective W/B ratio remains constant across all mixtures, preventing the recycled aggregates from absorbing the mixing water required for cement hydration and workability.

2.2.2 Research process

To meet all performance criteria, the experimental program is divided into three stages. Preliminary printability is assessed via flow table and pistol tests, followed by rheological characterization, compressive strength testing, and practical 3D printing trials.

Step 1 optimized W/B and S/B ratios by testing six reference mixtures (Table 4). Based on preliminary mix design optimization and in alignment with previous work on printable mortars [19, 58], W/B and S/B values were selected within ranges of 0.3–0.4 and 1.0–1.5, respectively.

Step 2 evaluated recycled sand substitution levels (0%, 25%, 50%, 75%, and 100% by weight), incorporating a superplasticizer to maintain printability. Each mix was then assessed via flow table, pistol, and compressive strength tests to determine its printability and mechanical performance. The spread diameter of this 3D printable cementitious material ranges from 15 to 20 cm [43, 59, 60].

Although typical civil construction applications only strictly require a compressive strength of around 30 MPa [61], designing the initial mix to achieve 50 MPa ($\pm 10\%$) in laboratory molded tests is necessary to counteract processing losses. In practice, the actual compressive strength of 3D-printed elements drops to only about 70–80% of conventionally cast specimens due to weak interlayer bonding [62–64]. Therefore, targeting a higher laboratory strength of 50 MPa ($\pm 10\%$) serves as a vital safety margin, ensuring that the final printed components on-site still successfully meet or exceed the minimum structural requirements after accounting for anisotropic printing weaknesses.

In Step 3, RCCF cement substitution levels (5%, 10%, and 15% by weight) were evaluated once the optimal recycled sand content was established. These final mixtures underwent comprehensive evaluation—including flow table, mechanical strength, and pistol tests—along with RheoCAD rheological analysis and 3D printing trials to define

Table 4 Initial reference mixtures

Mixture	W/B	S/B	%NS	Quantities (kg/m ³)		
				Cement	NS	Water
REF1	0.30	1.00	100%	1004	1004	301
REF2	0.35	1.00	100%	956	956	335
REF3	0.40	1.00	100%	913	913	365
REF4	0.30	1.50	100%	844	1266	253
REF5	0.35	1.50	100%	810	1215	284
REF6	0.40	1.50	100%	779	1168	311

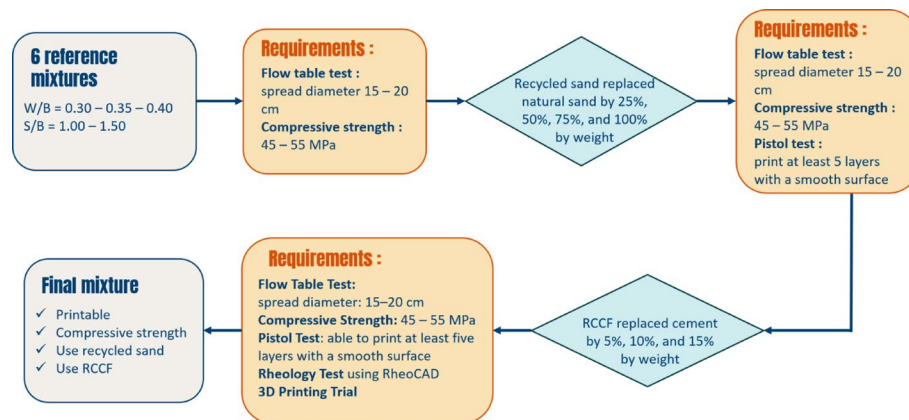


Fig. 4 The research process of this study

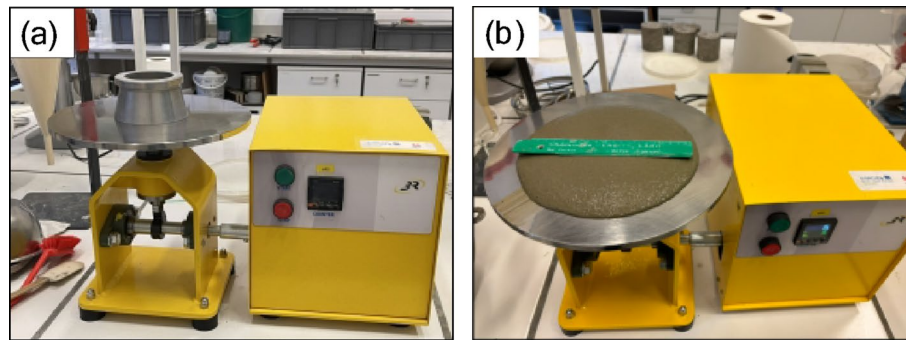


Fig. 5 (a) The flow table test, (b) sample on the flow table after raising 15 times

all critical performance parameters. Any potential impact of RCCF on the workability of the mixture will be adjusted using a superplasticizer.

RCCF is used as a partial substitution for cement primarily due to its physical filler effect. Physically, RCCF enhances particle packing density by filling interstitial voids, thereby releasing entrapped water to maintain adequate lubrication and favorable fresh rheological performance. A residual hydraulic or pozzolanic reactivity of the unhydrated cement phases within RCCF cannot be entirely excluded; however, this contribution, if present, remains unverified in the present study and is treated as an unverified hypothesis rather than an established mechanism of strength development. Therefore, RCCF can partially replace cement, reducing overall cement consumption without adversely affecting the printability and mechanical properties of the mortar.

The overall research process is illustrated in Fig. 4.

2.2.3 Flow table test

The first experiment performed is the flow table test (Fig. 5a), conducted in accordance with EN 13395-1:2002. This test evaluates the workability of the mortar by measuring its spread: after the table is lifted and dropped vertically 15 times, the diameter of the spread is recorded (Fig. 5b). The experiments were performed at least three times to ensure the most accurate results.

2.2.4 Pistol test

The pistol test (Fig. 6a), although a non-standard method, plays a crucial role in evaluating the buildability and extrudability of mortars in 3D printing technology [43]. In this procedure, a small specimen composed at least of five printed layers is produced to examine the material's behavior during the printing process.

The nozzle used in this study had a diameter of 20 mm. The printing process was carried out manually. The printed specimen had a plan dimension of 100 mm × 100 mm and a height of approximately 60–80 mm, depending on the behavior of the material.

A mixture was considered to exhibit satisfactory printability if it met the following criteria:

- Pumpability: The material could be extruded without blockage inside the extrusion pistol.
- Extrudability: The extruded filament was smooth and continuous, with minimal surface cracking.
- Buildability: The material was capable of supporting at least 5 successive layers without exhibiting signs of collapse, excessive deformation, or instability.

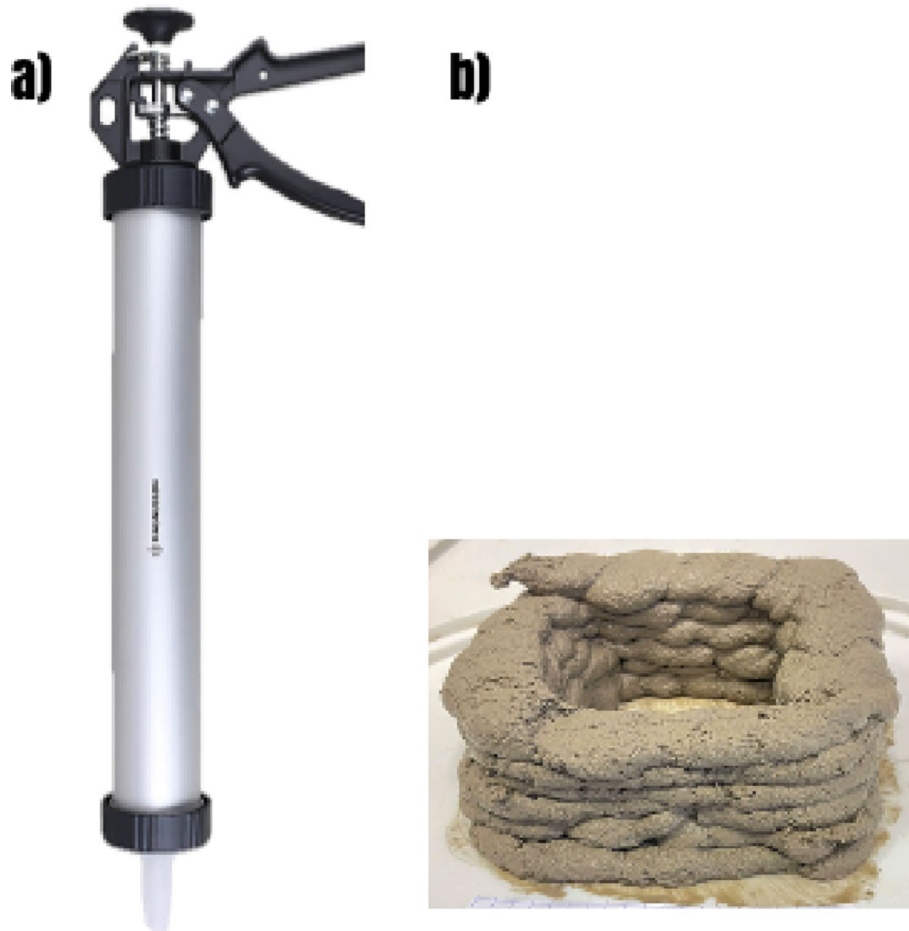


Fig. 6 (a) Pistol test, (b) printed sample from the pistol test

2.2.5 Compressive strength

The compressive strength of the mortar was evaluated using standard $4 \times 4 \times 16$ cm molds. Testing was conducted on the INSTRON 5585H1015 system. Measurements were performed three times, at 3, 7, and 28 days after casting.

The compressive strength testing was conducted on portions of prisms obtained after the flexural strength test, strictly adhering to the standard sequence specified in EN 196-1.

2.2.6 Rheological parameters measurement

Concrete and mortar are non-Newtonian fluids; the most common model to illustrate their behaviour is the Bingham model defined by Eq. (1):

$$\tau = \tau_0 + \mu \dot{\gamma} \quad (1)$$

where τ and τ_0 represent the shear stress and yield stress, respectively; μ is the plastic viscosity; $\dot{\gamma}$ is the shear rate.

The yield stress (τ_0) and viscosity (μ) are key parameters for 3D printing materials, which must be fluid enough for pumping and extrusion yet strong enough to support multiple layers. A material's suitability is assessed by pumpability, extrudability, and buildability, with pumpability and extrudability mainly determined by yield stress, and buildability influenced by both yield stress and viscosity.

The rheological properties of the mortar were measured using a RheoCAD rheometer (CAD Instrument), which is specifically designed to determine both the viscosity and yield stress of mortar. The instrument features a four-blade rotational system with a maximum capacity of 3 L, and the blade dimensions are illustrated in Fig. 7. The experiments were performed at least three times to ensure the most accurate results.

During testing, the RheoCAD records rotation speed (N, in rpm) and torque (T, in N-cm). Using these measurements along with the blade geometry, the shear stress (τ) and shear rate ($\dot{\gamma}$) are calculated according to Eqs. (2) and (3). Once these parameters are obtained, the two key rheological properties—yield stress (τ_0) and viscosity (μ)—are determined by applying the Bingham fluid model (as shown in the Fig. 8) [43, 65].

$$\dot{\gamma} = \frac{R_o^2 + R_i^2}{R_o^2 - R_i^2} \times 2 \pi N \quad (2)$$

$$\tau = \frac{R_o^2 + R_i^2}{4 \pi h R_o^2 R_i^2} \times T \quad (3)$$

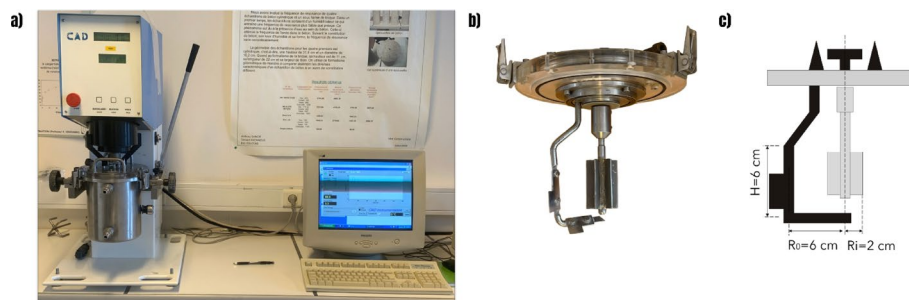


Fig. 7 Rheometer RheoCAD: (a) Overview of the device, (b) detailed view of the blade, and (c) schematic diagram with dimensions

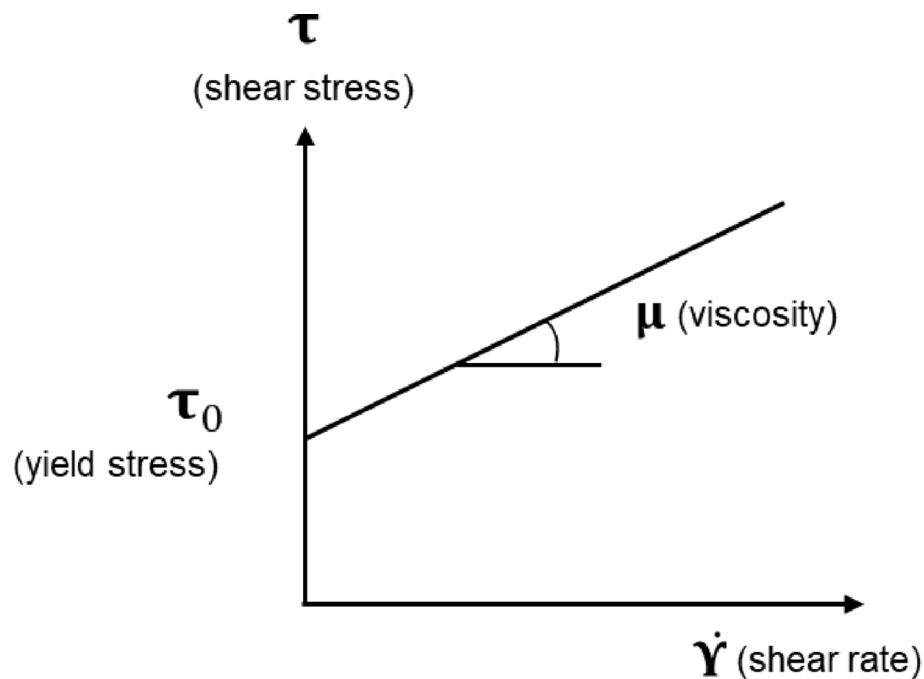


Fig. 8 The Bingham model

To perform these rheological measurements, a dedicated rheometer program is employed that uses a ramp-down stress protocol [66], specifically designed for the blade rheometer. This protocol begins with a pre-stress phase to ensure material homogeneity, followed by a gradual decrease in shear stress every 20 s. The process continues until the shear stress reaches zero rounds per minute (Fig. 9).

2.2.7 3D printing system

In this study, the Stoneflower 3D concrete printer was employed to evaluate the printability of the 3D-printed mix designs. The printing system consists of two main components: a 3-axis 3D printer and a material pump. The printing material is first prepared in a mixer and then transferred to the pump for extrusion. Once the material reaches the printer nozzle, the 3D printer reads the prepared G-code file to initiate the printing of the 3D element. The entire printing process is illustrated in Fig. 10.

The specimen used to evaluate the printability of the mixtures was a rectangular element with dimensions of 150 mm (height) x 170 mm (width) x 350 mm (length). Printing was executed layer by layer, with each layer having a height of 15 mm and a width of 45 mm. The printing process was performed using a nozzle with a diameter of 34 mm moving at a constant deposition speed of 75 mm/s. To feed the material, the pump maintained a volumetric flow rate of approximately 3.9 L/min at the printer inlet, while the initial pressure at the pump inlet was set to 7 bar. The distance from the nozzle to the previously deposited layer was exactly equal to the layer height of 15 mm.

3 Results and discussion

3.1 Determination of mix composition

Although numerous studies on mix design for 3D printing materials have been conducted worldwide, a unified standard for designing mixtures for this technology has

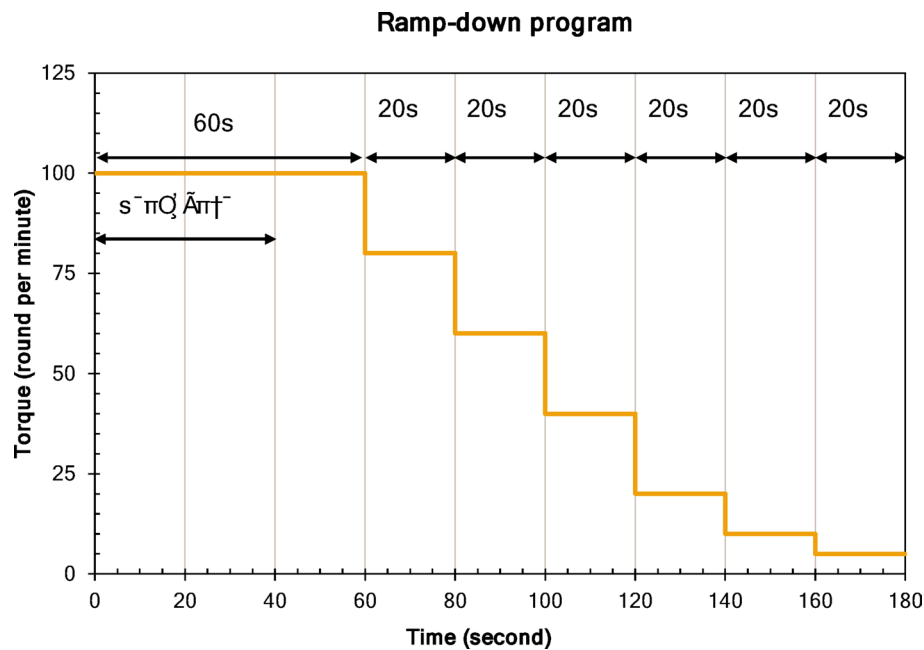


Fig. 9 The ramp – down program for the RheoCAD



Fig. 10 The printing process

not yet been established. In previous studies, researchers often determine the W/B ratio and S/B ratio by selecting relatively broad ranges and then evaluating the printability of the mixtures. Through this process, a suitable composition is identified that meets the requirements of the printing technology and is compatible with the available materials and printing equipment. This approach has proven to be an effective method for determining appropriate mix proportions.

Following this methodology, the present study compiles and reviews mix designs for 3D printed concrete reported in the literature in order to identify commonly used ranges of W/B and S/B ratios. Based on this analysis, reasonable intervals are selected for experimental investigation. Printability tests are then conducted in combination with rheological measurements to determine the optimal mix composition for the material system under study. Specifically, the W/B ratio is examined within the range of 0.30 to 0.40, with values of 0.30, 0.35, and 0.40, while the S/B ratio is selected within the range of 1.0 to 1.5, based on preliminary mix design optimization and in alignment with previous work on printable mortars [19, 58].

The mix compositions investigated in this phase are presented in Table 4.

To determine the printability of a mixture, the first step is to conduct a series of tests, including the flow table test, pistol test, and rheological measurements at 10 min after mixing. The 10-minute mark is chosen based on practical considerations of the printing process, as it typically corresponds to the time when printing begins. Printability is then evaluated using criteria such as spread diameter, yield stress, viscosity, and the results of the pistol test trial print.

Figure 11a illustrates the significant influence of the W/B and S/B ratios on the flowability of the mixture. Based on the spread diameter results from REF 1 to REF 3, a clear trend regarding the W/B ratio emerges: an increase in water content leads to more fluid-like behavior. This is clearly demonstrated by the substantial increase in the spread diameter, which expands from 10 cm for the REF 1 mixture to 30 cm for REF 3.

A higher W/B ratio increases the water film thickness around cement particles, reducing interparticle friction and weakening the flocculated network. This decreases the yield stress and viscosity, causing the material to deform under its own weight. Although pumpability and extrudability are improved, buildability is compromised because the deposited filament cannot retain its shape. These observations are consistent with the findings of M. Gurunandan et al. [67]. Furthermore, Hojae Lee et al. [68] recommended maintaining the W/B ratio within the range of 0.28–0.32 to ensure the stability of the printed filaments after extrusion.

A rheological behavior corresponding to a spread diameter of 30 cm is highly unsuitable for 3D concrete printing. As indicated by the properties of the REF 3 mixture in Table 5, this profile closely resembles a Newtonian fluid with a yield stress of nearly zero. Such a negligible yield stress results in extremely poor buildability, making the mixture incompatible with automated deposition [69].

Contrary to the fluid behavior observed in REF 3, REF 1 and REF 4 (the two mixtures with a W/B ratio of 0.3) exhibited excessively stiff and dry characteristics, with a spread diameter of only approximately 10 cm (Table 5). This behavior can be attributed to the insufficient free water content, which resulted in inadequate particle lubrication and the formation of a discontinuous cement paste phase. Although a W/B ratio of 0.30 has been commonly reported for 3D-printable cementitious materials, previous studies often incorporated mineral admixtures (e.g., fly ash) and superplasticizers to enhance the workability and flowability [70–72]. In this study, the fine aggregate size (maximum particle size of 2 mm) increased the water demand and reduced the effective

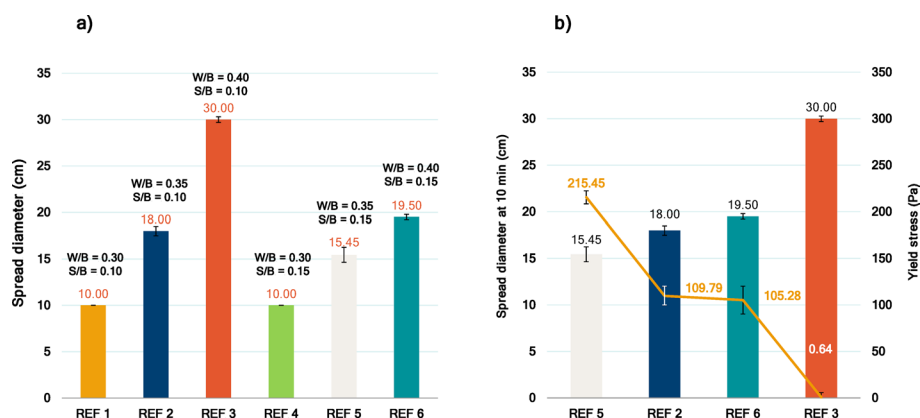


Fig. 11 Experimental results of: (a) the flow table test, and (b) the rheological parameters

Table 5 Experimental results of the flow table test, RheoCAD measurements, and the printing evaluation via pistol test

Mixture	Spread diameter (cm)	Spread diameter SD (cm)	Rheological equations	Yield stress SD (Pa)	Rheological parameters (τ_0 : yield stress and μ : viscosity)	Pistol test
REF1	10.00	0.00				Cannot be printed – the material is blocked
REF2	18.00	0.50	$y = 18.84x + 109.79$	10.00	$\tau_0 = 109.79$ Pa $\mu = 18.84$ Pa·s	Printable – smooth and continuous extrusion – suitable for printing multiple layers
REF3	30.00	0.30	$y = 3.69x + 0.64$	5.00	$\tau_0 = 0.64$ Pa $\mu = 3.69$ Pa·s	Cannot be printed – the material is too liquid
REF4	10.00	0.00				Cannot be printed – the material is blocked
REF5	15.45	0.80	$y = 34.67x + 215.45$	7.00	$\tau_0 = 215.45$ Pa $\mu = 34.67$ Pa·s	Printable – smooth and continuous extrusion – suitable for printing multiple layers
REF6	19.50	0.30	$y = 22.18x + 105.28$	15.00	$\tau_0 = 105.28$ Pa $\mu = 22.18$ Pa·s	Printable – smooth and continuous extrusion – good for printing multiple layers

W/B ratio. Consequently, these mixtures exhibited a predominantly solid-like behavior with extremely limited deformability and were excluded from further rheological characterization.

Regarding the S/B ratio, the decreasing trend in spread diameter observed for REF 5 and REF 6 compared with REF 2 and REF 3, respectively, indicates that increasing sand content reduces the flowability of the mixtures. This effect can be attributed to the reduction in available cement paste volume per unit of aggregate, resulting in a thinner lubrication layer around sand particles and increased interparticle friction. As a result, a denser granular skeleton is formed, leading to higher resistance to deformation and lower spread diameter [73]. This behavior is clearly demonstrated by the reduction from 30 cm to 19.5 cm when comparing REF 3 and REF 6.

The rheological results further confirm this transition in material behavior. While REF 3 exhibited a highly fluid-like response with negligible resistance to flow, REF 6 showed typical Bingham plastic behavior, characterized by a yield stress of 105.28 Pa and a viscosity of 22.18 Pa·s (Table 5). The increase in sand content therefore transformed the mixture from a highly deformable suspension into a more structured material with greater resistance to flow.

While limited conclusions can be drawn from the correlation between spread diameter and viscosity, the relationship between spread diameter and yield stress (Fig. 11b) provides clearer insights into the effects of W/B and S/B ratios on this key rheological parameter. The results show that increasing the S/B ratio within the investigated range increases the yield stress due to stronger aggregate interactions and reduced paste lubrication.

Comparing REF 2 and REF 3 in terms of water content demonstrates that increasing the W/B ratio reduces the yield stress, owing to the increased amount of free water and the weakened particle network within the mixture. Similar phenomena have also been reported by Le et al. [24]. In contrast, the comparison between REF 3 and REF 6, which

have the same W/B ratio of 0.40, shows that a higher S/B ratio leads to an increase in yield stress due to increased particle contact and friction.

These findings highlight the importance of optimizing yield stress to achieve a balance between buildability and extrudability in 3D concrete printing. Mohan et al. [73] emphasized this important consideration by showing that excessively high yield stress can make extrusion difficult, while insufficient yield stress can lead to poor layer stability after deposition.

Based on the evaluation of all three experiments, mixtures REF 2, 5, and 6 are printable. However, beyond printability requirements, compressive strength remains the primary design objective of this research. The target mechanical strength of this study is about 50 MPa ($\pm 10\%$) as discussed before.

The compressive strength results for the three mixtures are shown in Fig. 12.

REF 2 achieved a compressive strength of 92.01 MPa at 28 days. This high strength value is mainly attributed to the high binder content combined with a low W/B = 0.35. This result is also consistent with the findings of Sun et al. [74] and Rahul et al. [75], who reported compressive strengths of approximately 80–90 MPa for casted samples using mixtures with similarly low W/B ratios. Hou et al. [76] also indicated that a low W/B ratio is a key factor in achieving high compressive strength, while Le et al. [24] reported a compressive strength of approximately 110 MPa at 28 days for a mixture with a W/B ratio of 0.26. These findings are consistent with Abrams' law, which states that reducing the W/B ratio improves compressive strength [77].

For the objective of this study, REF 2 was excluded due to its relatively high cement content, accounting for approximately 30% of the mixture volume. REF 5 and REF 6 were considered more suitable because of their lower cement consumption. Although both mixtures exhibited comparable 28-day compressive strengths, REF 6 was selected over REF 5 as it showed a higher spread diameter, which is beneficial for printability. In the subsequent stages, recycled sand will be incorporated, potentially increasing the

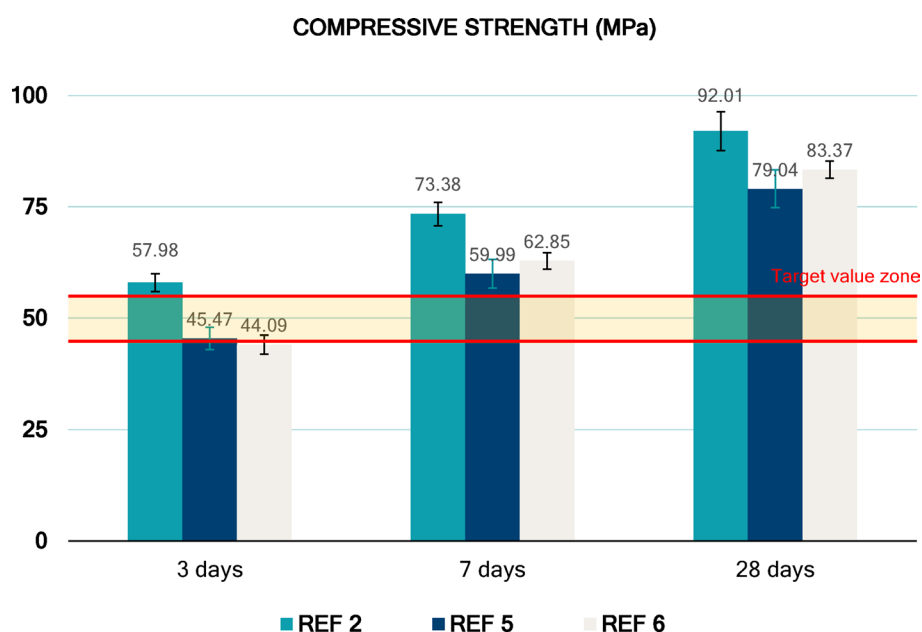


Fig. 12 Compressive strength of REF 2, REF 5, and REF 6

yield stress and altering the viscosity of the mixture [48]. Therefore, a mixture with better flowability was selected to minimize the risk of printing failure.

3.2 Effect of RS and RCCF on 3D printed mortar performances

To evaluate the influence of RS and RCCF on the performances of 3D printing mortar, various ratios of RS and RCCF were used to replace NS and cement to determine the optimal dosage for the validated mix composition. The proportions used to study the effects of RS and RCCF are presented in Table 6. Mixtures RS 07 through RS 10 incorporate recycled sand at substitution levels ranging from 25% to 75% by weight, and mixtures FIN 05 through FIN 15 represent the incorporation of RCCF at substitution levels ranging from 5% to 15% by weight. Since recycled sand has higher water absorption than natural sand, the water absorbed by the recycled sand was compensated for to keep the W/B ratio constant, as discussed earlier.

Figure 13 illustrates the correlation between flowability and yield stress, while Table 7 presents the results of the pistol test, spread diameter, and rheological equations.

For the mixtures incorporating recycled sand from RS 07 to RS 10, the results are consistent with previously established relationships showing that high proportions of water absorbing components typically reduce flowability and increase yield stress. This trend remains valid when replacing NS with RS. As the RS content increases from 25% to 100% (corresponding to mixes RS 07 to RS 10), Fig. 13 clearly demonstrates that higher RS substitution levels lead to lower spread diameters and higher yield stress values.

The incorporation of RS plays a crucial role in increasing the yield stress of the mixtures, while ensuring that all proportions maintain printable. This behavior is clearly demonstrated by the pistol test results presented in Table 7.

Regarding extrudability, the increase in RS does not significantly impair this characteristic. The printed filaments remain continuous, stable, and free of tearing or rupture. Although prior studies have indicated that using higher amounts of recycled sand affects the surface of the printed filament [78, 79], the current pistol test results do not exhibit this trend.

Buildability is also highly satisfactory across the tested mixtures from RS07 to RS10. Most printed layers are stable, capable of being stacked without collapsing. For a preliminary evaluation, the results obtained from these mix designs are highly positive [43].

While pumpability cannot be quantitatively measured in the pistol test due to the absence of a force-recording sensor, the increase in yield stress associated with higher RS content, as shown in Table 7, requires a higher extrusion force to initiate material flow. Indeed, during testing, a noticeably greater pressure had to be applied to the pistol to extrude the material as the RS content increased. This observation aligns with physical expectations and is consistent with previous findings reported in the literature [24].

Overall, despite the higher yield stress requiring greater pumping pressure to overcome yield stress to flow, all mixtures remain printable and meet the printability criteria. The pistol test thus confirms the reliable printability of the four mixtures from RS07 to RS10.

The next factor to consider is the strength of the RS 07 and RS 10 mixtures to evaluate the influence of RS on them. Figure 14a shows the compressive strength from RS 07 to RS 09. In general, observing the results obtained from the chart, it is noticeable that increasing the content of recycled sand used reduced the compressive strength of the

Table 6 Mixtures incorporating RS

Mixture	W/B	S/B	Quantities (kg/m ³)										Superplasticizer (%wob)
			%NS	%RS	%Cement	%RCCF	Cement	NS	RS	RCCF	Water	Added water	
RS 07	0.40	1.50	75%	25%	100%	0%	770	866	289	0	308	40	0.99
RS 08	0.40	1.50	50%	50%	100%	0%	761	571	571	0	304	79	1.35
RS 09	0.40	1.50	25%	75%	100%	0%	753	282	847	0	301	117	1.51
RS 10	0.40	1.50	0%	100%	100%	0%	744	0	1117	0	298	155	1.70

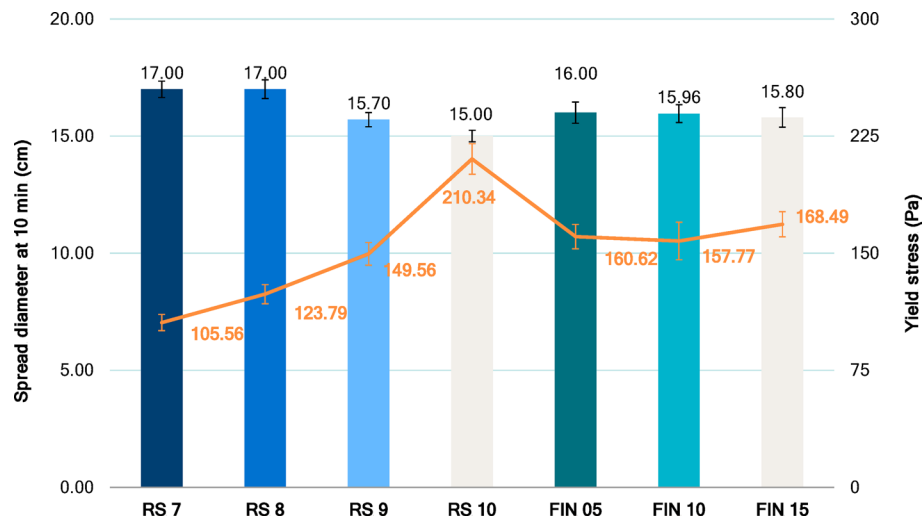


Fig. 13 Relationship between spread diameter and yield stress for mixtures incorporating RS and RCCF

mixture, from 64 to 42 MPa, corresponding to a decrease of 5.5 MPa for every 25% of RS used to replace NS. This decrease can be explained by the fact that the structure of recycled aggregate particles always has lower strength than that of natural aggregate particles [80]. This trend is consistent with Zhao et al. [81], who observed a quasi-linear decrease in compressive strength as fine recycled concrete aggregate replacement increased, attributing this to the higher porosity and water demand of the recycled aggregates.

Among the studied mixtures, the RS 10 mixture failed to meet the target compressive strength and was therefore excluded from the study, leaving three mixtures that satisfy the target strength. To maximize environmental friendliness, RS 9 was selected because this mixture meets the strength requirement while utilizing the highest content of RS among the remaining mixtures. This 75% replacement level is also supported by several studies on 3D concrete printing. Recent studies have further confirmed the feasibility of recycled sand incorporation in 3D printed concrete, highlighting its potential to enhance sustainability by reducing the dependence on natural sand resources [82], Ding et al. [46] also demonstrated the feasibility of incorporating recycled sand into extrusion-based 3D printed concrete, showing that high recycled sand replacement levels can be adopted while maintaining acceptable mechanical performance.

The RS 7 and RS 8 mixtures were not excluded from the study because they still satisfy both rheological and strength requirements. If RS 9 fails to meet the criteria, RS 7 and 8 will be used.

The mixtures using RCCF are presented in Table 8, where RCCF was used to replace cement from 5% to 15% by weight.

The results presented in Fig. 13 indicate that the incorporation of RCCF exerted a negligible influence on the spread diameter of the mixtures from FIN 05 to FIN 15. Regarding printability in the pistol test, all three mixtures exhibited similar behavior. Pumpability, extrudability, and buildability were all well demonstrated. All three mixtures showed a smooth printed filament, required similar pressure to extrude from the print head, and maintained a stable shape after printing (Table 7).

Regarding rheological parameters, FIN 05 and FIN 15 exhibit similar viscosities, indicating that RCCF does not affect viscosity up to a 15% replacement level. Similarly, the yield stress values of FIN 05 (160.62 Pa), FIN 10 (157.77 Pa), and FIN 15 (168.49 Pa) vary

Table 7 Rheological parameters, spread diameter, and the pistol test results for mixtures RS 07–09 and FIN 05–15

Mixture	Spread diameter (cm)	Spread diameter SD (cm)	Rheological equations	Yield stress SD (Pa)	Rheological parameters (τ_0 : yield stress and μ : viscosity)	Pistol test
RS 07	17.00	0.35	$y = 22.54x + 105.56$	5.20	$\tau_0 = 105.56 \text{ Pa}$ $\mu = 22.54 \text{ Pa}\cdot\text{s}$	 Printable – smooth surface – low printing pressure – suitable for printing multiple layers
RS 08	17.00	0.40	$y = 18.84x + 123.79$	6.10	$\tau_0 = 123.79 \text{ Pa}$ $\mu = 18.84 \text{ Pa}\cdot\text{s}$	 Printable – smooth surface – low printing pressure – suitable for printing multiple layers
RS 09	15.70	0.30	$y = 27.56x + 149.56$	7.30	$\tau_0 = 149.56 \text{ Pa}$ $\mu = 27.56 \text{ Pa}\cdot\text{s}$	 Printable – smooth and continuous extrusion – moderate printing pressure – suitable for printing multiple layers
RS 10	15.00	0.25	$y = 20.14x + 210.34$	9.80	$\tau_0 = 210.34 \text{ Pa}$ $\mu = 20.14 \text{ Pa}\cdot\text{s}$	 Printable – smooth and continuous extrusion – high printing pressure – suitable for printing multiple layers
FIN 05	16.00	0.45	$y = 25.58x + 160.62$	7.80	$\tau_0 = 160.62 \text{ Pa}$ $\mu = 25.58 \text{ Pa}\cdot\text{s}$	 Printable – smooth and continuous extrusion – moderate printing pressure – suitable for printing multiple layers
FIN 10	15.96	0.38	$y = 26.94x + 157.77$	12.00	$\tau_0 = 157.77 \text{ Pa}$ $\mu = 26.94 \text{ Pa}\cdot\text{s}$	 Printable – smooth and continuous extrusion – moderate printing pressure – suitable for printing multiple layers

Table 7 (continued)

Mixture	Spread diameter (cm)	Spread diameter SD (cm)	Rheological equations	Yield stress SD (Pa)	Rheological parameters (τ_0 : yield stress and μ : viscosity)	Pistol test
FIN 15	15.80	0.42	$y = 25.35x + 168.49$	8.10	$\tau_0 = 168.49 \text{ Pa}$ $\mu = 25.35 \text{ Pa.s}$	 Printable – smooth and continuous extrusion – moderate printing pressure – suitable for printing multiple layers

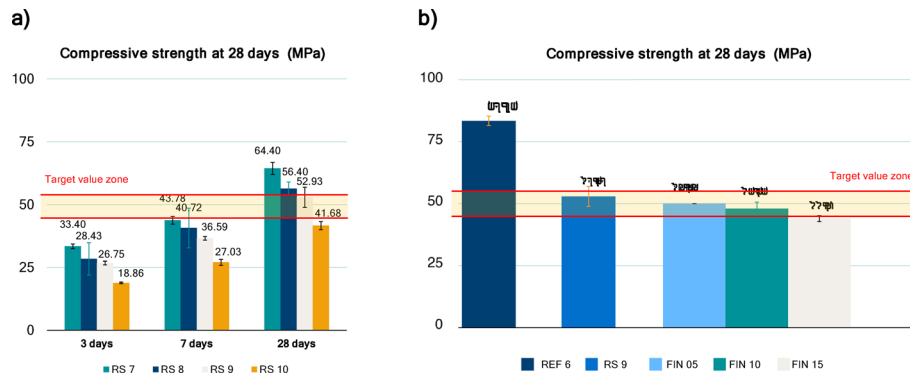


Fig. 14 Compressive strength of the studied mixtures: **(a)** 3, 7, and 28 days for RS 7–10; **(b)** 28 days for REF 6, RS 9, and FIN 05–15

within a narrow range. This minor variation is likely within experimental tolerance and presents no significant technical difference in printability.

Combined results from the spread diameter, pistol test, and rheometer show that 5% to 15% RCCF replacement has no noticeable impact on printability. This aligns with the behavior of limestone powder in concrete [83, 84]. At moderate cement replacement levels (5% to 20%), filling, lubrication, dilution, and particle packing effects maintain or slightly improve workability. Ultimately, mineral additions like RCCF do not significantly affect mixture rheology when used at appropriate replacement levels.

To evaluate the mechanical performance of the FIN 05 to FIN 15 mixtures, their compressive strengths are assessed and presented in Fig. 14b. For comparison, these results are plotted alongside those of RS 9 (identical W/B and S/B ratios, 100% cement, and 75% recycled sand) and REF 6 (100% cement and 100% natural sand). A clear trend emerges: increasing the RCCF content progressively reduces compressive strength, with each 5% increment corresponding to a decrease of approximately 2 to 3 MPa. This is illustrated by the drop from 52.93 MPa for the RS 9 to 44.01 MPa for the FIN 15. In summary, combining up to 75% RS replacement with the addition of RCCF leads to a distinct strength reduction, dropping from the reference value of 83.37 MPa (REF 6) down to approximately 50 MPa.

This suggests that the effect of RCCF on the mixtures is relatively similar to the filler effect provided by materials such as nano clay [85] and limestone powder [86]. RCCF cannot compensate for the reduction in strength caused by its incorporation. Therefore, the amount of unhydrated components remaining in RCCF is likely limited, and their contribution to the final strength is difficult to identify and appears to be insignificant. Consequently, RCCF should only be used as a partial replacement at an appropriate level, as excessive replacement may lead to a significant dilution effect due to the reduction in clinker content available for C–S–H gel formation [87].

Based on the results, the FIN 15 mixture failed to reach the target strength and only two mixture satisfied all 3D printing criteria: FIN 05 and FIN 10, having 28-day compressive strengths of 50.00 MPa and 47.99 MPa, respectively. Hence, FIN 10 and FIN 05 will be used on the lab-scale printer for trial printing.

3.3 3D printing trial evaluation

To evaluate the conclusions regarding the printability of FIN 05 and FIN 10, laboratory printing tests were conducted to verify whether these two mixtures meet the necessary

Table 8 Mixtures incorporating RCCF

	Quantities (kg/m ³)						RCCF	Water	Added water	Superplasticizer (%wob)			
	Mixture	W/B	S/B	%NS	%RS	%Cement					%RCCF	Cement	NS
FIN 05	0.40	1.50	25%	75%	95%	712	05%	281	844	37	300	117	151
FIN 10	0.40	1.50	25%	75%	90%	672	10%	280	840	75	299	116	151
FIN 15	0.40	1.50	25%	75%	85%	633	15%	279	837	112	298	116	151

a) FIN05



b) FIN10

**Fig. 15** The actual printing performance of (a) FIN 05 and (b) FIN 10

requirements for 3D printing technology. Due to the physical constraints of the laboratory printer, the maximum height achieved was limited to that shown in Fig. 15. Both mixtures exhibited comparable printability, successfully achieving up to 10 printed layers without signs of collapse. The printed surfaces were smooth and consistent, meeting the standard requirements for 3D printing. All specimens were printed approximately ten minutes after the initial mixing process.

Regarding pumpability, this property depends on various factors of the printing system, such as the pipeline configuration, movement speed, and nozzle diameter. According to [88] Zhang et al., a printable mixture should possess low viscosity and moderate yield stress to enable smooth transport through the delivery system. However, it remains difficult to define precise limits for these parameters, as the printable ranges reported in existing studies vary. In the context of this study, the FIN 05 and FIN 10 mixtures exhibited yield stress values between 160.62 and 157.77 Pa and viscosity values between 25.58 and 26.94 Pa.s. Corresponding to these rheological parameters, the excellent pumpability of both FIN 05 and FIN 10 was demonstrated by their highly consistent and consistent deposition, with no occurrences of pipeline clogging during the printing process.

Extrudability refers to the ability of a mixture to produce a continuous and stable printed filament. This property depends on factors such as the type and particle size distribution of aggregates, the W/B ratio, and the geometry of the printer nozzle, and other printing parameters. An optimal combination of yield stress and viscosity is also essential to maintain extrusion stability. Both FIN 05 and FIN 10 used fine aggregates smaller than 2 mm, shared the same W/B ratio, and exhibited similar rheological properties as previously discussed. Based on the results shown in Fig. 15, it can be concluded that these mixtures demonstrate great compatibility with the printing system used in this study.

Buildability refers to the ability of a mixture to sustain multiple printed layers without collapsing. This property is primarily governed by the yield stress of the material. A higher yield stress generally enhances buildability; however, excessively high values can negatively affect extrudability and pumpability.

In this study, the yield stress values of FIN 05 and FIN 10 were approximately 160.62 Pa and 157.77 Pa, respectively, which were sufficient to achieve stable printing of up to 10 layers without any signs of deformation or collapse. It should be emphasized that the 10-layer limit is imposed by the printer capacity rather than representing the actual limit of the mixture's buildability.

The maximum printed height achieved in this study was approximately 150 mm. Since the printing parameters, including nozzle diameter (34 mm), deposition speed (75 mm/s), and target layer height (15 mm), were held constant throughout the deposition process, and since the maximum printed height (150 mm) closely matched the design height, layer geometry can be considered consistent throughout the print. Visual inspection of the printed specimens (Fig. 15) confirmed the absence of visible bulging, necking, or progressive layer widening, which would otherwise indicate accumulating deformation under self-weight. These observations indicate that the investigated mixtures exhibited stable layer deposition and satisfactory stacking capability within the current printing height and under the present laboratory conditions.

To provide broader context, these results can be compared with existing literature regarding yield stress in 3D-printable mixtures. Rehman et al. identified a "printable zone" for concrete between 100 and 700 Pa [19]. Furthermore, Weng et al. reported successful printing of up to 40 layers with a high yield stress of 492.7 Pa and a viscosity of 16.65 Pa.s, while Kruger et al. achieved 59 layers with 1532 Pa [20, 89]. Other researchers, such as Le et al., observed ranges of 300–900 Pa [24]. In contrast, Zhang et al. reported a practical yield stress range of 100–200 Pa [25], which aligns closely with the present findings. Similarly, the "printable zone" defined by Tran et al. [90] suggested that a yield stress between 268.9 and 313.6 Pa is required for adequate buildability.

Although the rheological parameters of FIN05 and FIN10 fall within the printable ranges reported in previous studies, these results alone cannot confirm that the mixtures would achieve comparable buildability performance to those reported in large-scale printing investigations. Yield stress and viscosity are important indicators for mixture design; however, buildability is also influenced by other factors, including structural recovery, elastic modulus development, layer interaction, and resistance to progressive deformation during printing [10, 91–93].

Nevertheless, regarding the printability and potential applications of FIN05 and FIN10, both formulations exhibit highly stable rheological behavior that ensures smooth material transport from the pump to the nozzle at the laboratory scale, demonstrating great pumpability and extrudability. While further comprehensive buildability performance remains to be fully characterized, laboratory-scale observations confirm their reliable printability and structural stability during the successful stacking of a 10-layer component.

4 Conclusion

Based on the research conducted, the following conclusions can be drawn regarding the use of ecofriendly materials in 3D concrete printing mixtures:

- The optimal W/B and S/B ratios identified in this study are 0.40 and 1.50, respectively. Lower W/B ratios resulted in insufficient flowability and poor extrudability due to high yield stress, while higher ratios compromised buildability by reducing shape stability. Although previously reported ranges provide useful guidance, only a specific combination within these ranges can meet all requirements for 3D printing performance. These findings demonstrate that optimal mix proportions are highly dependent on material characteristics. Additionally, differences in printing systems further affect rheological requirements. Therefore, mix design for 3D printable mortar must be tailored to specific materials and printing conditions rather than relying solely on generalized empirical ranges.
- The results show that up to 75% recycled sand can be used while maintaining suitable rheological properties, printability, and compressive strength for 3D printing. Although higher substitution levels have been reported, this study targets a relatively high strength of approximately 50 MPa with a margin of plus or minus 10% and includes RCCF, which increases system complexity. As a result, the 75% substitution represents a balanced optimization between printability, mechanical performance, and sustainability.
- Findings demonstrate that utilizing up to 75% recycled sand preserves the necessary rheological properties, printability, and compressive strength for 3D printing. Although literature reports higher replacement ratios, this study rigorously targets a robust compressive strength of approximately 50 MPa ($\pm 10\%$) while managing the system complexities introduced by RCCF. Within this framework, the high water absorption of the recycled aggregates was proactively offset during mixing to ensure continuous characteristic.
- The results show that up to 10% RCCF can be used as a partial cement substitution while maintaining adequate rheological properties, printability, and overall performance. At this level, the 28 day compressive strength remains about 90% of the reference mix, indicating minimal loss in mechanical performance. RCCF has not been proven to contain components that participate in reactions during the hydration process.
- RCCF does not significantly affect the rheological behavior of the mixtures, with mixtures containing 5% to 15% RCCF demonstrating equivalent rheological indices.
- Mixtures containing 75% recycled sand and from 5% to 10% RCCF met all 3D printing requirements. They demonstrated great extrudability and pumpability. While full scale structural evaluations were beyond the scope of this study, the optimized yield stress and viscosity guaranteed sufficient buildability, preventing layer deformation during laboratory scale deposition.

The engineering significance of this research lies in providing a dual valorization pathway for regional construction and demolition waste streams within bound cementitious systems for digital construction. Practically, the developed green mortar is highly suitable for nonstructural or semistructural prefabricated elements, urban architectural furniture, and low rise structural components. By significantly reducing reliance on both natural river sand and ordinary Portland clinker, this mix design offers a concrete technical solution to mitigate the carbon footprint and resource depletion associated with modern automated construction.

5 Limitations and future research directions

While the immediate feasibility and fresh state stability of the optimized mixture have been confirmed at a laboratory scale, certain limitations remain to be addressed to facilitate full scale industrial implementation:

- This study focused primarily on the macro mechanical and fresh rheological properties; consequently, comprehensive microstructural investigations and long term durability assessments, including drying shrinkage, freeze thaw resistance, and carbonation behavior, were not conducted.
- The structural buildup behavior was restricted by laboratory equipment capacities, meaning that full scale structural performance under continuous high volume pumping remains unquantified.
- It is acknowledged as a limitation that both the RS and RCCF used in this study were sourced from a single batch and localized within Belgium. While this approach ensured consistency within the experimental program, it does not account for the inherent material variability typically found across different batches of recycled construction and demolition waste due to fluctuations in source, crushing processes, and original concrete composition. Furthermore, because the collection, treatment, and logistics were regional, the physical and chemical characteristics reflect local specificities and are not necessarily representative of recycled aggregates globally. Consequently, transferring or applying this mix design to other context or regions requires careful consideration and optimization of the proportions to account for local material variations.
- While the printability assessment was successfully evaluated using a customized testing protocol tailored to our specific printing system, it is acknowledged that rheological behavior may vary when transferred to different printing setups or alternative testing configurations.

To bridge these gaps and transition this technology from laboratory to practical execution, future research should focus on clarifying the interlayer bonding mechanisms and anisotropic weaknesses under actual structural deposition conditions. Furthermore, rigorous investigations into long term durability and validation via large scale, automated industrial 3D printing systems are highly recommended to guarantee the structural robustness and service life of the printed elements.

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Author contributions

Bao Ta Minh Phuong: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. Luc Courard: Conceptualization, Methodology, Supervision, Project administration, Writing – review & editing. Dung Tien Nguyen: Conceptualization, Methodology, Supervision, Formal analysis, Validation.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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