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Impact of industrial waste fillers in self-compacting mortars: A comparative analysis of mechanical performance

Ahmed Messaoud Djebara ^{*,1,2,a}, Mohamed Mouli ^{1,b}, Karim Belmokretar ^{1,c}, Ramdane Chihaoui ^{1,d}, Yassine Senhadji ^{1,3,e}, Ahmed Soufiane Benosman ^{1,4,f}, Mehdi Seghiri ^{5,g}

¹Department of Civil Engineering, National Polytechnic School of Oran, Laboratory of Materials LABMAT, Algeria

²Department of Architecture, University of Algiers 1, Algeria

³Department of Civil Engineering, University of Mascara, Algeria

⁴Ecole Supérieure en Sciences Appliquées de Tlemcen, Algeria

⁵Faculty of Sciences and Technology, University of Tamanghasset, Algeria

Article Info	Abstract
<p>Article History:</p> <p>Received 18 June 2025</p> <p>Accepted 20 Aug 2025</p> <p>Keywords:</p> <p>Industrial waste; Glass; Brick; Ceramic; Self-compacting mortars; Hydration heat; Mechanical performance</p>	<p>This study investigates the viability of utilizing non-biodegradable industrial waste streams specifically ground glass, crushed brick, and sanitary ceramics as alternative fillers in self-compacting mortars (SCMs). A conventional SCM mixture incorporating traditional limestone filler served as the control benchmark. The research assessed the influence of substituting conventional fillers with waste-derived materials, varying their proportions while maintaining a constant cement content. The experimental results showed that the inclusion of alternative fillers enabled the target slump flow values to be achieved with a lower water-cement ratio, thus reducing water demand. However, the mortars with brick and ceramic fillers had longer mini-V-funnel flow times. Analysis of the hydration heat revealed that brick and ceramic fillers accelerated early hydration reactions, whereas glass fillers exhibited a delayed reactivity. Mortars containing these alternative fillers showed significant mechanical strength increases over time; compressive strength and dynamic modulus of elasticity increased significantly. After 365 days of curing, compressive strength values increased by 34% and 37% for mortars containing brick and ceramic fillers, respectively, and by 31% for those incorporating glass fillers, relative to the control mortar. These findings highlight the promising potential of valorizing industrial waste materials as efficient, economical, and environmentally sustainable alternatives to conventional limestone fillers in SCMs.</p>

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1. Introduction

The construction industry represents one of largest consumers of raw materials globally and is a significant contributor to environmental degradation. Notably, cement production a fundamental component of concrete is responsible for approximately 8% of worldwide carbon dioxide emissions [1]. Concurrently, the accumulation and disposal of non-biodegradable industrial waste, such as glass, brick, and sanitary ceramic residues, present formidable environmental challenges across numerous regions. These materials occupy valuable landfill space and pose long-term ecological threats.

*Corresponding author: a.messaouddjebara@univ-alger.dz

^aorcid.org/0009-0001-4506-6391; ^borcid.org/0000-0001-7199-4928; ^corcid.org/0000-0001-8184-9898;

^dorcid.org/0000-0002-6507-1446; ^eorcid.org/0000-0003-0678-3424; ^forcid.org/0000-0002-0344-020X;

^gorcid.org/0000-0001-5332-4840.

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Self-compacting mortars (SCMs), derived from the technological advances of self-compacting concrete (SCC), represent a significant innovation within construction material science [2]. Characterized by exceptional flowability, homogeneity, and stability, SCMs possess the ability to spread and consolidate solely under gravitational forces, obviating the need for mechanical vibration. Their carefully regulated viscosity enables them to efficiently fill formwork and envelop reinforcing elements without inducing segregation, blocking, or bleeding phenomena [3]. Achieving these functional properties necessitates a high content of fine materials (cement and fillers), elevated dosages of chemical admixtures, and a relatively low water-to-binder ratio [4].

In SCM formulations, fillers play a vital role in enhancing rheological performance, optimizing fresh-state workability, controlling cement dosage, and regulating the heat generated during hydration, thereby reducing the risk of cracking in the hardened mortar. Conventionally, limestone fillers are preferred due to their ability to densify the granular skeleton, enhance cohesion, and limit particle segregation [5]. However, limestone fillers present certain limitations, such as geographically constrained availability, high transportation costs, and the absence of pozzolanic activity, which restricts their capacity to enhance the long-term mechanical properties of the mortar. In response to these shortcomings, extensive research has focused on identifying alternative filler materials. Various natural pozzolans and mineral additions, including natural pozzolan [6], dolomite [7], fly ash [8], silica fume [4], and metakaolin [9], among other industrial by-products, have been investigated.

Among these alternatives, waste glass, brick, and ceramic materials are attracting increasing attention due to their favorable chemical compositions and inherent pozzolanic activity. Glass waste, composed predominantly of silica (73%), sodium oxide (13%), and lime (10%), demonstrates significant pozzolanic reactivity, beneficial for mortar and concrete applications [10]. Previous investigations into the incorporation of glass powder into SCC have yielded divergent results. Some studies reported reductions in slump flow and compressive and flexural strengths when glass powder was added at dosages of 5%, 10%, and 15% [11], while others found a significantly enhanced flexural strength by up to 6.85% [12].

Brick and ceramic waste materials are generated primarily from production defects (ranging from 15% to 30% of manufactured products) or demolition activities. Composed mainly of silica (SiO_2) and alumina (Al_2O_3), these materials exhibit notable pozzolanic activity. Prior research demonstrated that the partial replacement of cement with brick powder in SCM formulations could yield compressive strengths comparable to or even exceeding those of traditional mixes [13]. Additional studies observed that brick powder improved both compressive and flexural strength, albeit with an increase in viscosity without significantly impairing workability [14].

It is important to highlight that while previous investigations predominantly focused on utilizing such waste-derived materials as partial cement replacements, relatively few studies have explored their use as fillers. In this context, Zengfeng Zhao and al. [15] evaluated the substitution of limestone fillers with brick powder in SCMs and noted an initial reduction in compressive strength at 7 days, subsequently offset by pozzolanic reactions leading to strength recovery after 28 days.

Our study pioneers the use of industrial waste as fillers ($< 200 \mu\text{m}$) rather than cement substitutes ($< 80 \mu\text{m}$), enabling substantially higher waste incorporation: 150 kg/m^3 of fillers versus just $90\text{--}135 \text{ kg/m}^3$ in typical cement substitution (20-30%). This dual-benefit approach achieves 30-40% grinding energy savings due to less demanding particle size requirements, and remarkable mechanical enhancements. These gains stem from the synergistic interplay between granular packing effects and the waste materials' latent pozzolanic activity, which collaboratively refine the matrix microstructure into a denser, more resilient composite.

The primary objective of the present study is to assess the feasibility of employing ground glass, brick, and ceramic waste as alternative fillers in self-compacting mortar formulations. The originality of this work lies in the specific application of these materials as fillers, rather than as cement substitutes, coupled with a comprehensive evaluation of their influence on both early-age and long-term performance properties. The specific objectives pursued are as follows:

- To characterize the physicochemical properties of the alternative fillers derived from industrial waste.
- To investigate the effects of these fillers on the rheological behavior of fresh SCMs.
- To evaluate their influence on hydration heat evolution.
- To monitor the development of mechanical properties, including compressive and tensile strength, and dynamic modulus of elasticity, over a period extending to 365 days.

By valorizing industrial waste within high-performance construction materials, this study supports the advancement of circular economy principles, contributing both to environmental sustainability and the enhancement of material performance

2. Experimental Program

2.1 Materials

2.1.1 Cement

The cement utilized in this study was a Portland cement classified as CEM I 52.5 R, conforming to Algerian standard NA 442, which is harmonized with European standard EN 197-1 [16]. This cement grade was selected due to its high early strength development and purity ($\geq 95\%$ clinker) to clearly isolate the effects of industrial waste fillers on high-performance mortars, while reflecting regional construction practices where this cement class dominates demanding structural applications. The chemical composition, detailed in Table 1, indicates a significant presence of calcium oxide (CaO, 63.25%) and silicon dioxide (SiO₂, 25.35%), these components are primarily responsible for the mechanical strength development through the formation of calcium silicate hydrate (C-S-H) gel as a result of hydration reactions.

2.1.2 Fillers

The fillers investigated were derived from various types of recovered industrial waste:

- Glass Fillers (Gl): Sourced from discarded green glass bottles collected from uncontrolled disposal sites. The bottles were subjected to cleaning, crushing, and fine grinding to achieve an appropriate particle size distribution.
- Brick Fillers (Br): Obtained from defective products rejected by a brick manufacturing facility due to non-conformity with quality standards.
- Ceramic Fillers (Cr): Retrieved from sanitary ceramic production waste, processed similarly to the brick fillers.
- Limestone Fillers (LS): Employed as the reference filler, representing the material most frequently employed in production processes of mortars and self-compacting concrete



Glass (Gl)

Brick (Br)

Ceramic (Cr)

Fig. 1. Various types of waste materials

All waste-derived materials underwent preliminary cleaning and crushing using a hammer mill. Subsequently, they were oven-dried at 105°C for 24 hours and finely ground in a ball mill to achieve a particle size below 200 µm. The grinding duration was adjusted individually for each filler type to achieve a fineness comparable to that of the limestone filler. Notably, brick fillers required extended grinding times, while glass fillers, constrained by the available equipment, were processed to the highest achievable fineness. Figure 1 presents the appearance of the waste materials before and after processing. The chemical and physical characteristics of fillers and cement are presented in Tables 1 and 2, respectively. Scanning Electron Microscopy (SEM), combined with Energy Dispersive X-ray Spectroscopy (EDS), was employed to investigate the morphology and elemental composition of the fillers (Figure 2).

Table 1. Chemical composition of the fillers and cement (%)

(%)	LS	Gl	Br	Cr	CEMI
CaCO ₃	94.5	-	-	-	-
CaO	-	7.40	9.20	9.61	63.26
SiO ₂	2.95	74.52	49.26	54.32	25.36
Al ₂ O ₃	1.46	5.5	29.41	27.67	5.77
Fe ₂ O ₃	0.02	0.4	2.50	1.2	0.30
MgO	0.15	0.55	2.26	0.37	1.76
Na ₂ O	0.3	11.02	0.75	1.64	0.05
TiO ₂	0.023	0.09	0.59	0.37	0.124
P ₂ O ₅	0.026	0.04	0.17	0.12	0.078
Cl	0.05	0.003	0.011	0.005	0.03
K ₂ O	0.08	0.45	1.66	0.87	0.45
Mn ₂ O ₃	13ppm	39ppm	0.01	0.02	38ppm
Cr ₂ O	10ppm	19ppm	0.04	0.01	5ppm
SO ₃	-	0.04	0.11	0.04	2.83
L.O.I	43.2	1.28	2.48	1.46	2.97
(SiO ₂ +Al ₂ O ₃ + Fe ₂ O ₃)	-	80	81.14	83.4	-

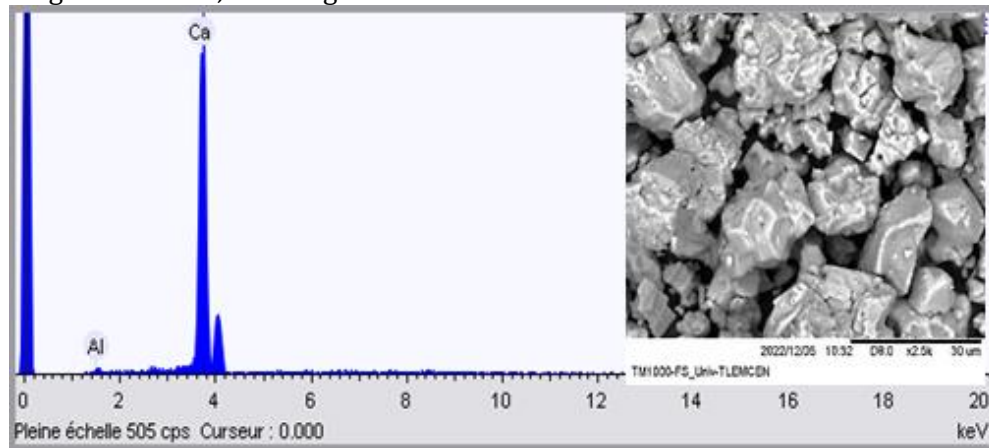
Table 1 provides a comprehensive analysis of the chemical composition (% mass) of the conventional limestone filler (LS), alternative waste-derived fillers (glass-GI, brick-Br, ceramic-Cr), and Portland cement (CEM I 52.5 R). These data reveal critical insights into the intrinsic properties governing filler performance in self-compacting mortars (SCMs): Dominant Oxides and Reactivity:

- Limestone Filler (LS): Comprises 94.5% CaCO₃ (inert carbonate phase), with negligible reactive oxides (SiO₂ + Al₂O₃ + Fe₂O₃ = 4.43%). This confirms its role as a physically functional but chemically inert filler, primarily enhancing particle packing without contributing to pozzolanic reactions.
- Glass (GI): High SiO₂ (74.52%) and Na₂O (11.02%) content aligns with typical soda-lime glass. The combined pozzolanic oxides (SiO₂ + Al₂O₃ + Fe₂O₃ = 80%) signify latent reactivity, though low CaO (7.40%) and Al₂O₃ (5.5%) limit early gel formation.
- Brick (Br): Rich in SiO₂ (49.26%) and Al₂O₃ (29.41%), yielding high pozzolanic oxide content (81.14%). Elevated Al₂O₃ promotes C-A-H/C-A-S-H gel formation, accelerating strength development.
- Ceramic (Cr): Highest pozzolanic oxide fraction (83.4%), with balanced SiO₂ (54.32%) and Al₂O₃ (27.67%). This optimal composition explains its superior pozzolanic indices (I₂₈=0.87, I₉₀=0.99, Table 2).

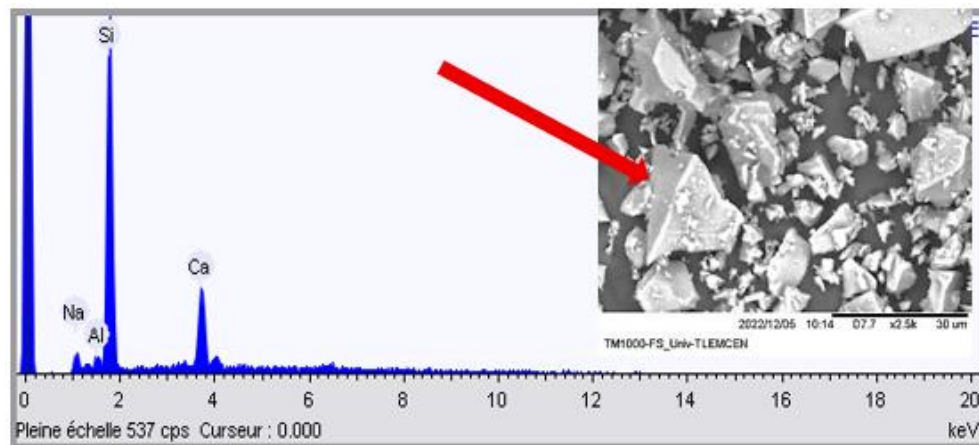
Spectroscopy (EDS) for the alternate fillers glass, brick, and ceramic, as well as the reference filler limestone. These analyses yield vital understanding of:

- iMorphology and Physical Structure:
- Glass Filler (GI): Particles with angular and smooth surfaces (red arrow) explain low interparticle friction as enhancing workability. Their limited surface area slows down the pozzolanic reaction.

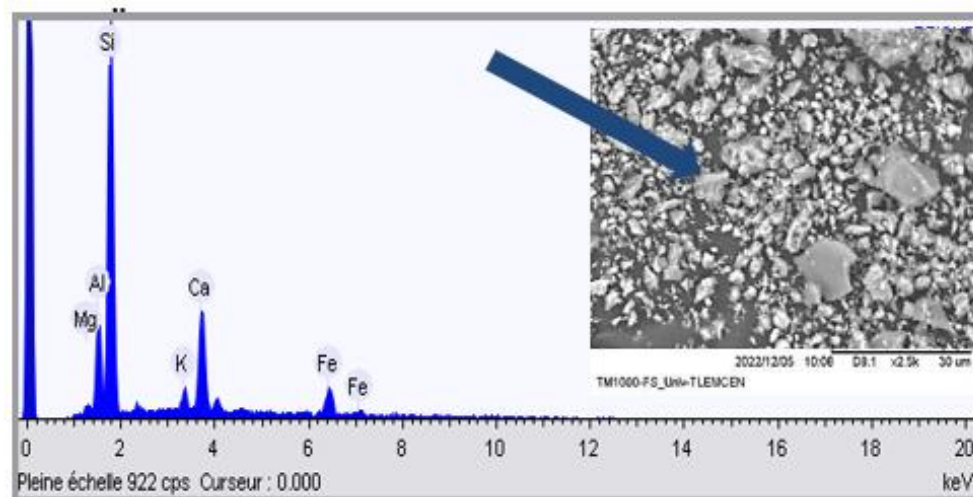
- Brick and Ceramic Filler (Br): Depicted particles and irregular porous microstructure (blue arrow) improve specific surface area, aiding nucleation in early hydration. This chemically enhances the pozzolanic index and structurally contributes to micro-defect-rich C-A-S-H gel formation.
- Limestone (LS): No arrows indicate the rounded and compact morphology which suggests its inert nature. This explains the filler's role as a rheologically-active filler without pozzolanic activity.
- Mineralogical Composition (EDS): EDS mappings validate Table 1 data:
- High silica (Si) in Gl (74.52%) and aluminosilicates (Al/Si) in Br/Cr drive differential pozzolanic reactivity. Elevated alumina (Al) in Br/Cr (29.41%/27.67%) promotes C-A-H/C-A-S-H gel formation, enabling microstructural densification



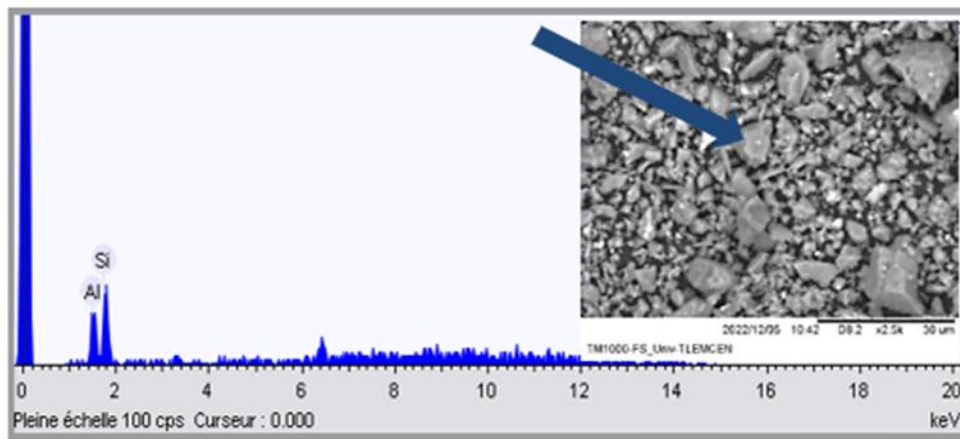
Lime Stone



Glass



Brick



Ceramic

Fig. 2. Results of SEM and EDS analyses of the filler materials

Table 2. Physical properties of fillers and cement

Physical character.	Color	Specific gravity	Refusal 45 $\mu\text{m}\%$	i_{28}	i_{90}
LS	White	2,62	28	-	-
Gl	White	2,51	32,2	0,73	0,78
Br	Red	2,56	22,5	0,83	0,93
Cr	White	2,53	17	0,87	0,99
CEMI	White	3,1	-	-	-

Furthermore, the pozzolanic activity indices (i_{28} and i_{90}) corroborated the reactivity of these fillers, particularly for ceramics, where values of 0.87 and 0.99 were observed at 28 and 90 days, respectively.

2.1.3 Sands and admixtures

Two types of sand were combined for mortar preparation: fine siliceous sand and coarse calcareous sand. A blend of fine sand and coarse sand was selected to achieve optimal spreadability and fluidity necessary for self-compacting mortar characteristics. The sands exhibited the following physical properties: Fineness Modulus of 2.2; Apparent Density of 1305 kg/m^3 ; Absolute Density of 2500 kg/m^3 ; and Sand Equivalent (SE) of 88. A third-generation polycarboxylate-based superplasticizer, compliant with the NF EN 934-2 standard [17], was used at a saturation dosage corresponding to approximately 5% of the cement weight. This elevated dosage aimed to minimize water content while enhancing long-term mechanical performance. All mortar mixtures were prepared using distilled water.

2.2 Formulation of Mortars

Each filler type (brick, ceramic, limestone, and glass) was incorporated into separate self-compacting mortar formulations. The quantity of water added to each mix was adjusted to maintain a target slump flow diameter within the range of 24 to 26 cm (specifically, $250 \pm 10 \text{ mm}$), as specified in the test methodology. Table 3 provides a summary of the mortar compositions utilized.

Table 3. Different formulations of self-compacting mortars (g)

SCM	LS	Gl	Br	Cr
Cement			450	
Filler	150	150	150	150
Water	180	168.75	157.5	157.5
F Sand			720	
C Sand			480	
SP			22.5	

2.3 Test Methods

2.3.1 Fresh State Properties

The fresh-state behavior of the mortars was evaluated following the EFNARC guidelines [18] to quantify workability adjustments required for alternative fillers. Immediately after mixing, the slump flow was measured using a mini-cone, and flow time was determined using a mini-V-funnel apparatus. In order to ensure comparable slump flows (targeted at 250 ± 10 mm) across different formulations, the water-to-cement (W/C) ratio was adjusted for each mortar while maintaining a constant superplasticizer dosage.



Fig. 3. Rheological property measurement: (a) Mini-slump cone; (b) Mini V-funnel apparatus

2.3.2 Fresh Density

The fresh (or bulk) density of the self-compacting mortars was determined in accordance with NF EN 1015-6 [19] as a critical indicator of volumetric efficiency, especially given the lower specific gravity of waste fillers (Table 2). For each formulation, a cylindrical container with a known volume of 1 litre was filled with fresh mortar without the application of compaction or vibration, then weighed. The apparent density was determined by dividing the mass of the mortar by the volume of the container. For each mixture, three measurements were conducted, and the average value was recorded.



Fig. 4. Fresh density measurement using a calibrated cylindrical container

2.3.3 Heat of Hydration

The evolution of hydration heat was assessed in accordance with standard NF EN 196-9 [20] using a semi-adiabatic Langavant calorimeter to identify acceleration/delay effects induced by waste fillers reactivity. A mortar sample weighing 1500 g was placed into a calibrated cell coated with a

thin oil film to prevent external moisture exchange. Temperature measurements were recorded every 10 minutes over a period of 72 hours.



Fig. 5. Semi-adiabatic hydration heat monitoring using a Langavant calorimeter

2.3.4 Mechanical Strength

Mechanical properties of the mortars, including compressive and flexural strength, were characterized using prismatic specimens measuring $4 \times 4 \times 16 \text{ cm}^3$, prepared according to NF EN 196-1 [21] to evaluate long-term performance gains from pozzolanic reactions. Tests were conducted after curing periods of 2, 7, 28, 90, 270, and 365 days. Specimens were cured in lime-saturated water at a constant temperature of 20°C until testing. Testing at 2 days, a key stage of primary hydration, assesses the early strength development of CEM I 52.5 R cement and fillers reaction (nucleation), essential for validating rapid-cycle applications like accelerated formwork removal or precast concrete production.

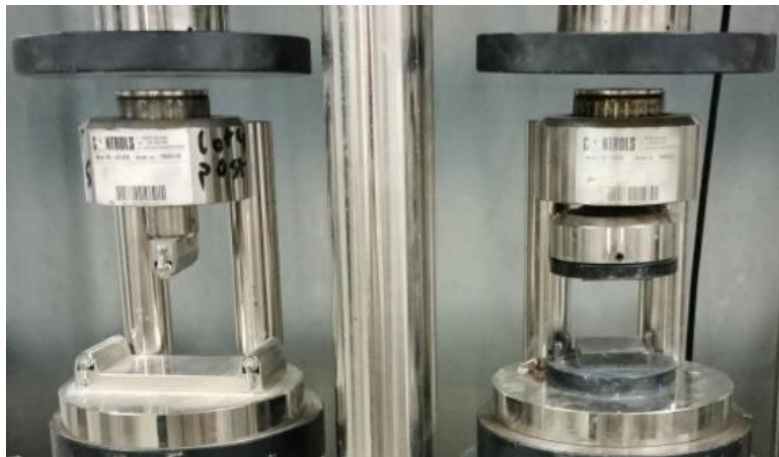


Fig. 6. Mechanical strength testing on prismatic specimens ($4 \times 4 \times 16 \text{ cm}^3$)

2.3.5 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity (E_d) was evaluated non-destructively using the Ultrasonic Pulse Velocity (UPV) method, in accordance with ASTM C597[22] to assess microstructural densification resulting from filler interactions, complementing mechanical strength data. This technique has been widely recognized as an effective non-destructive method for assessing the elastic properties and quality of cementitious materials, as documented by Malhotra and Carino [16]. Measurements were conducted on the same prismatic specimens ($4 \times 4 \times 16 \text{ cm}^3$) used for compressive strength testing, at both 28 and 365 days of curing, prior to mechanical failure testing.



Fig. 7. Non-destructive measurement of dynamic modulus of elasticity (E_d) via ultrasonic pulse velocity

3. Results and Discussion

3.1 Fresh Properties Fresh Density

The mini-slump spread is widely regarded as the most indicative parameter for evaluating the flowability of self-compacting mortars. As shown in Table 4, all SCM mixtures achieved slump flow diameters within the acceptable range of 24 to 26 cm, conforming to EFNARC recommendations [18].

It was observed that mortars incorporating brick and ceramic fillers required a lower water content (approximately 35% relative to the mass of cement) compared to mortars utilizing limestone fillers, which necessitated about 40%. This reduction in water demand for waste-derived fillers is a significant finding. However, as this inherently alters the water-cement (w/c) ratio, it is expected to directly influence key mechanical properties. Consequently, comparisons between filler types must consider that observed differences in strength (compressive, flexural) and durability are likely attributable both to the filler characteristics and the resulting w/c ratio difference. This underscores the importance of reporting mix design parameters when evaluating filler effects in SCMs. It is noteworthy that Corinaldesi and Moriconi [23] reported contrasting results, indicating an increase in water demand with higher levels of filler substitution. Such discrepancies are likely attributable to differences in filler fineness and morphological characteristics between their study and the current work. In general, a reduction in water demand is associated with improved mechanical performance.

Regarding flow time measurements using the mini-V-funnel, mortars containing limestone fillers exhibited optimal flow (9 s), while brick and ceramic fillers showed extended flow times (20 s and 14 s, respectively) exceeding EFNARC's strict recommended range of (7–11 s) for self-compacting mortars. This deviation, particularly critical for brick filler (+82% above limit), indicates reduced flowability attributed to higher surface adhesion of these waste materials. This reduced flowability stems from the inherently higher surface adhesion tendencies of brick and ceramic fillers, attributed to three key factors:

- *Particle Morphology*: Angular shard-like structures (Fig. 2) increase interparticle friction and physical water trapping [24].
- *Surface Roughness*: Microscale asperities enhance capillary forces and binder adsorption [25].
- *Chemical Reactivity*: Surface hydroxyl groups (-OH) from $\text{Al}_2\text{O}_3/\text{SiO}_2$ -rich compositions (Table 1) exhibit hydrophilic behavior, competing with superplasticizer molecules for water interaction [26]. In contrast, glass fillers (despite angularity) demonstrate smoother surfaces and lower chemical affinity, resulting in closer-to-limit flow times (12 s).

Table 4. Fresh state properties of self-compacting mortars incorporating different fillers

SCMs	LS	Gl	Br	Cr
W/C	0.40	0.375	0.35	0.35
Spreading (cm)	24.2	25.6	25.4	25.6
Mini V-funnel (s)	9	12	20	14
Fresh density (g/cm ³)	2.35	2.31	2.33	2.32

3.2 Fresh Density

The lower fresh density observed in mortars containing glass fillers is attributed to the inherently lower specific gravity of glass (2.51 g/cm³) compared to that of limestone filler (2.62 g/cm³). Although this density difference is modest, it can nonetheless influence key hardened- state properties such as thermal conductivity and acoustic insulation performance.

These results align with those reported by Felekoğlu et al [27], who documented a reduction in the fresh density of self-compacting mortars upon the incorporation of pozzolanic materials with densities lower than that of cement. Similarly, Uysal and Sumer [28] noted that the use of alternative fillers in self-compacting concrete led to a marginal reduction in fresh density an outcome potentially beneficial for applications where reduced weight is advantageous.

3.3 Heat of Hydration and Heat Flow

Figures 8 and 9 present the temperature and cumulative heat evolution curves during hydration process, while Table 5 summarizes key parameters including early activation metrics (Q_{10h} , T_{10h}), peak hydration parameters (T_m , t , Q_m), and percentage increases relative to control.

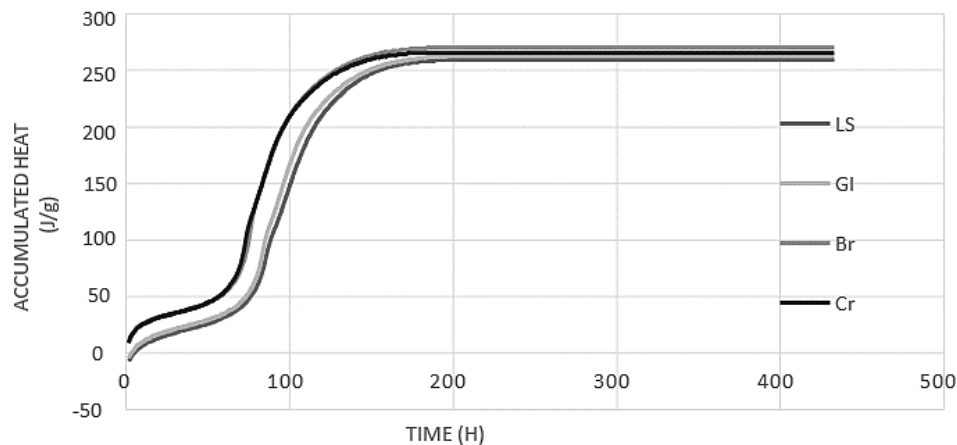


Fig. 8. Accumulated heat

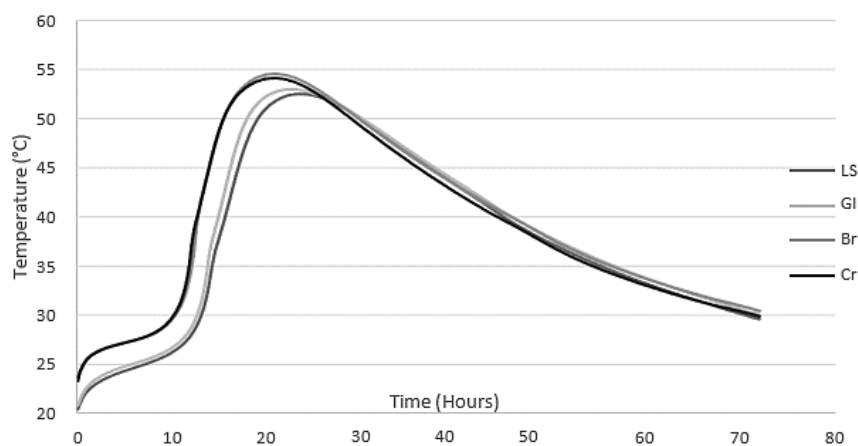


Fig. 9. Released heat

The results indicate that mortars incorporating brick and ceramic waste experienced significantly accelerated heat release within the first 10 hours of hydration, as quantitatively demonstrated by:

- Cumulative heat at 10 hours: Brick-filled mortar (Br) released of 55 J/g, ceramic-filled mortar (Cr) of 56 J/g, 67-70% higher than limestone control (LS of 33 J/g) and glass-filled mortar (Gl of 36 J/g).
- Temperature differential at 10 hours, Br and Cr mortars reached 29.82°C and 29.63°C respectively, exceeding LS (26.24°C) by 3.39-3.58°C (Fig. 9).

This acceleration stems from a nucleation effect: the fine, reactive particles ($d < 200 \mu\text{m}$) provide abundant preferential sites for nucleation of C-S-H phases. Specifically:

- Surface Area Amplification: High specific surface area (17 and 22.5% $< 45 \mu\text{m}$, Table 2) creates nucleation substrates [29].
- Template Effect: Al/Fe-rich surfaces (Table 1: 27.6 and 29.4% Al_2O_3) align Ca^{2+} and silicate ions, accelerating early gel growth [30].

This early acceleration culminated in peak temperatures of 54.6°C (Br) and 54.1°C (Cr) at 20.8 hours markedly higher and earlier than LS (52.5°C at 23.4 hours). The nucleation effect of fine, reactive particles ($\text{SiO}_2 + \text{Al}_2\text{O}_3 > 80\%$, Table 1) promoted rapid C-S-H formation, while glass fillers exhibited delayed reactivity due to their smoother, less reactive surfaces. Conversely, mortars containing glass fillers exhibited delayed hydration kinetics and lower early heat release. Despite these initial differences, the cumulative heat output of all mortar formulations converged after 72 hours. Furthermore, mortars containing ceramic and brick fillers reached their peak temperatures approximately at 21 hours, whereas mortars with limestone and glass fillers attained peak temperatures at around 22.5 hours.

Table 5. Characteristics of Hydration for the various self-compacting mortars

SCM	LS	Gl	Br	Cr
Q_{10h} (J/g)	33	36	55	56
% Q_{10h}	-	9.1	66.66	69.7
$T^\circ 10h$ (°C)	26.24	26.7	29.82	29.63
Q_m (J/g)	260	263	270	265
% Q_m	-	1.15	3.85	1.92
$T^\circ m$ (°C)	52.52	52.99	54.56	54.13
$tT^\circ m$ (h)	23.35	22.51	20.84	20.85

These observations are attributed to the nucleation effects provided by fine brick and ceramic particles, which enhance early-stage cement hydration. It is well established that nucleation phenomena are influenced by filler fineness and their affinity with hydration products [30].

Wild et al. [31] reported that partial replacement of cement with metakaolin accelerates the hydration process due to the rapid formation of pozzolanic products. Similarly, Kadri et al. [32] and Berodier and Scrivener [33] highlighted the significant role of particle fineness and mineral composition in promoting early hydration.

The present findings suggest that oxides present in the brick and ceramic fillers actively interacted with calcium hydroxide (CH) generated during hydration, accelerating the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels, thereby contributing to the enhanced initial heat release

3.4 Evolution of Mechanical Properties

Compressive strength is a critical indicator of mortar performance, influenced by variables such as water-to-cement (W/C) ratio, cement content, sand properties, and filler characteristics. Mechanical strength tests aimed to validate the trends observed in hydration heat behavior. Previous investigations involving brick [13,14], ceramic [34,35], and glass [12,36,37] as cement substitutes have demonstrated their pozzolanic potential.

As illustrated in Figure 10, compressive strength values for all mortar formulations consistently increased over time, with no strength reductions observed at any curing age. Mortars containing brick and ceramic fillers exhibited higher early-age strengths at 2 and 7 days, indicating accelerated strength development.

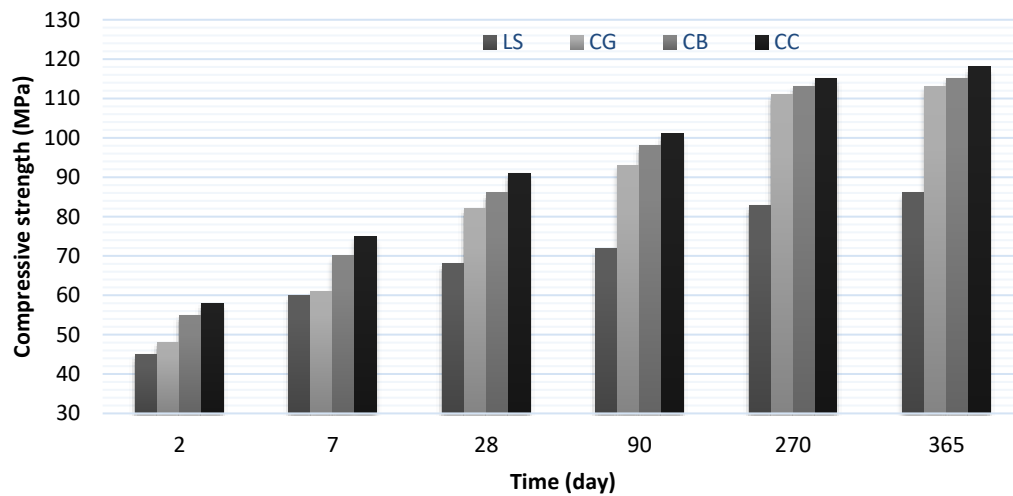


Fig. 10. Compressive strength of SCMs

At later stages, particularly after 365 days of curing, mortars incorporating brick and ceramic fillers achieved compressive strengths 34% and 37% higher, respectively, than the control mortar. Similarly, mortars incorporating glass fillers exhibited a 31% strength increase compared to the control. It is important to note that the pozzolanic reactions associated with brick and ceramic fillers were activated at early ages, affirming their nucleation effects. In contrast, glass fillers demonstrated delayed pozzolanic activity, with significant contributions to strength development observed primarily after 28 days of curing.

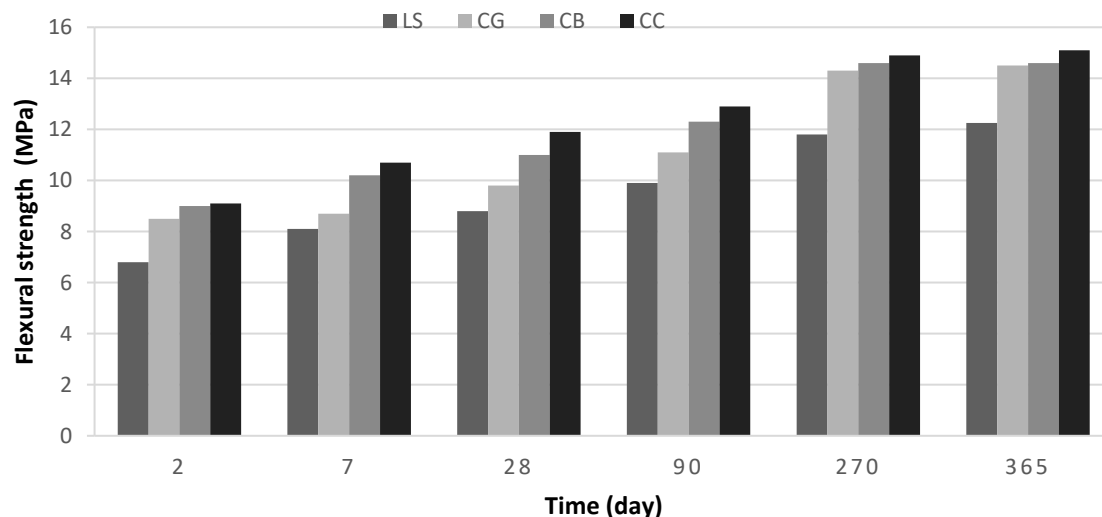


Fig. 11. Flexural strength of SCMs

The mechanical performance hierarchy (ceramic: +37% > brick: +34% > glass: +31% at 365 days) stems from differential chemical reactivity: Ceramic (Al_2O_3 of 27.7%) and brick (Al_2O_3 of 29.4% and Fe_2O_3 of 2.5%) fillers catalyze early C-A-S/H and C-A-F/H gel formation through aluminous sites, yielding +20% higher 7-day strength versus glass. Conversely, glass filler (SiO_2 of 74.5%) exhibits delayed alkaline dissolution (>28 days) restricted to homogeneous C-S-H gels, compounded by unfavorable particle size (32.2% retained at $45\mu\text{m}$) and smooth vitreous surfaces that limit pozzolanic reactivity (i_{90} of 0.78 vs. 0.99 for ceramic). Figure 11. Presents the evolution

of flexural strength which mirrored the trends observed for compressive strength, thus reinforcing the reliability of the results.

The superior long-term performance of mortars containing brick and ceramic fillers can be attributed to the lower W/C ratios, enhanced microstructural densification, and pozzolanic reactions leading to formation of C-A-H and C-A-S-H gels, especially due to high alumina content [14,19]. On the other hand, glass fillers, characterized by low alumina content, primarily facilitated the delayed generation of secondary C-S-H gels after prolonged curing periods. Notably, all mortars incorporating industrial waste-derived fillers achieved compressive strengths exceeding 80 MPa at 28 days. According to the ACI 363R-10 report [38], these mortars qualify as high-performance mortars (HPMs), given that the threshold for high-strength classification typically starts at 55 MPa and may vary regionally. In contexts where conventional concretes routinely reach 62 MPa, mortars achieving strengths in the range of 83–103 MPa are considered high-performance. Accordingly, the mortars produced in this investigation demonstrate mechanical performance consistent with HPM standards

3.5 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity (E_d), determined via the UPV technique, measures the propagation speed of ultrasonic waves through the material, where faster wave passage reflects denser and stiffer microstructures, resulting in higher E_d values. As noted by Neville [39], this non-destructive technique offers valuable information about the internal structure and mechanical properties of cementitious materials. The evolution of E_d over time for various SCM formulations is presented in Table 6.

Table 6. Dynamic Modulus of Elasticity (E_d , GPa) of SCMs

SCM	LS	Gl	Br	Cr
28days	46.4	47.0	50.8	49.2
365days	50.5	53.3	56.1	55.1

Consistent with compressive strength trends, E_d increased progressively across all formulations up to 365 days of curing, reflecting continued hydration and pozzolanic reactions that enhance matrix densification. This time-dependent evolution aligns with findings by Benaicha et al. [40], who observed similar patterns in self-compacting concrete incorporating various mineral additions. At all ages, mortars incorporating alternative fillers demonstrated notably higher E_d values than the reference mortar (SCM LS). At 28 days, relative increases in E_d were recorded as +1.24% for SCM Gl, +9.44% for SCM Br, and +5.86% for SCM Cr. These enhancements became more pronounced at 365 days, reaching +5.59%, +11.11%, and +9.16%, respectively. These results are consistent with research by Kou and Poon [41], who reported enhanced elastic properties in concrete containing recycled glass powder.

The superior E_d values observed in mortars with waste-based fillers can be ascribed to the development of a denser and more refined microstructure, attributed to both the physical filler effect and the pozzolanic reactivity of glass, brick, and ceramic powders. According to Mehta and Monteiro [42] the generation of additional calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels leads to a stiffer matrix with reduced porosity, thereby facilitating faster ultrasonic pulse propagation and resulting in higher calculated E_d values. This microstructural refinement has been confirmed by Yusuf et al. [43] using scanning electron microscopy on mortars containing pozzolanic materials.

The ranking of mortars based on dynamic modulus (SCM Br > SCM Cr > SCM Gl > SCM LS) closely parallels that observed for compressive strength, reinforcing the well-established correlation between these two properties in cementitious systems. This strong correlation between E_d and compressive strength is well-established for cementitious materials, as demonstrated by Popovics [44] and Trtnik et al. [45], who found that both properties are fundamentally linked to the quality and density of the hydrated paste and the interfacial transition zone.

The results confirm that the incorporation of industrial waste fillers not only enhances the mechanical performance but also significantly improves the stiffness of self-compacting mortars—an outcome particularly beneficial for structural applications where high rigidity and minimal deformation as emphasized by Breyse [46] in his comprehensive review on non-destructive assessment of concrete structures. Enhancements in E_d of up to 11.11% were recorded at 365 days for mortars incorporating brick-based filler.

4. Conclusion

This study systematically investigated the potential for valorizing industrial waste streams namely ground glass, sanitary ceramic, and brick waste as alternative fillers in self-compacting mortar (SCM) formulations. Based on the experimental results obtained, the following key conclusions are drawn:

- For the target slump flow (250 ± 10 mm), mortars with brick/ceramic fillers achieved comparable fluidity at reduced water-cement ratios (0.35 vs. 0.40 for limestone filler), indicating lower water demand. However, these mixes exhibited V-Funnel flow times exceeding EFNARC limits (20 s and 14 s vs. 9 s for control), revealing higher viscosity. Optimization of superplasticizer dosage or particle gradation is recommended.
- Mortars with waste-derived fillers showed marginally lower fresh densities (2.31 to 2.33 g/cm³) compared to limestone-based mixes (2.35 g/cm³), attributable to the lower specific gravity of glass (2.51), brick (2.56), and ceramic (2.53) versus limestone (2.62). This reduction, while modest (<2%), may benefit weight-sensitive applications.
- The use of brick and ceramic fillers accelerated the early hydration process, as evidenced by peak temperature measurements occurring at 21 hours, in contrast to 22.5 hours for mortars containing limestone and glass fillers.
- Mortars formulated with alternative fillers exhibited significant long-term improvements in mechanical strength. After 356 days of curing, compressive strengths increased by 37% and 34% for brick and ceramic fillers, respectively, and by 31% for glass fillers, relative to the reference mortar.
- The incorporation of waste-derived fillers led to a marked enhancement in the dynamic modulus of elasticity, indicative of the formation of a denser and stiffer microstructural framework. Notably, brick-filled mortars exhibited the highest improvement, with E_d values increasing by up to 11.11% at 365 days.
- Among the fillers evaluated, ceramic fillers demonstrated superior performance across most criteria, attributable to their high fineness and favorable chemical composition, which promoted pozzolanic activity.

Overall, the findings underscore the considerable potential of valorizing industrial waste materials as efficient and sustainable alternatives to traditional fillers in SCMs. The integration of these materials not only mitigates environmental impacts associated with waste disposal and resource extraction but also enhances the mechanical properties of mortars to a level consistent with high-performance standards.

Future research should aim to optimize filler dosage levels and explore the synergistic effects of combining multiple waste-derived fillers to further enhance performance and broaden the applicability of SCM technologies.

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