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Concrete Strength Evaluation Using Manufactured Sustainable Binary-Cement (SI): New Approach Case Study

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Abstract

The production of sustainable binary cement represents an innovative approach in blended cement manufacturing, aligning with environmental objectives by reducing the reliance on ordinary Portland cement and supporting waste disposal efforts. This study explores the partial replacement of cement with high-fineness powders derived from crushed and ground clay brick (CB) and window glass (WG) waste materials, used at replacement levels of 5%, 10%, and 15%. These materials were processed using a storming machine to achieve the desired particle fineness and incorporated into the cement to create what is referred to as sustainable cement (SI). The resulting binary cement formulations were evaluated and found to comply with the setting time, compressive strength, and chemical specifications outlined in ASTM C595. To further assess their performance, the sustainable cements were tested in concrete mixtures designed for three compressive strength levels—2000 psi, 5000 psi, and 7000 psi—in accordance with ACI 211.1, representing low, medium, and high strength applications, respectively. Two groups of mix designs were developed: MSI-B5, MSI-B10, MSI-B15 (with CB powder replacing 5%, 10%, and 15% of cement), and MSI-G5, MSI-G10, MSI-G15 (with WG powder at the same replacement levels). The results demonstrated notable improvements in compressive strength at the low-strength level. Specifically, cumulative strength increases were recorded as 15.8%, 21.9%, and 13% for MSI-B5, MSI-B10, and MSI-B15, respectively, and 12.2%, 15.5%, and 8.1% for MSI-G5, MSI-G10, and MSI-G15, respectively, when compared to the reference mix. In addition to compressive strength, enhancements in flexural and splitting tensile strengths were also observed, exhibiting a strong correlation with compressive performance. These findings support the potential of sustainable binary cement—utilizing CB and WG powders—as a viable and environmentally friendly alternative in concrete production across varying strength classes.

Keywords: Sustainable-Binary-Portland Cement (SI); Clay-Brick (CB); Glass-Window (GW).

1. Introduction

Sustainable development has become a global priority in the field of concrete construction, prompting researchers to explore environmentally friendly alternatives such as green concrete [1–3]. This approach not only offers ecological and economic benefits in concrete production but also facilitates waste recycling by repurposing materials like clay brick [4–6]. The traditional process of manufacturing cement clinker involves the thermal decomposition of calcium carbonate and the combustion of fossil fuels, which collectively generate approximately 1.25 tons of CO_2 per ton of cement produced [7–9]. Furthermore, the cement industry's high energy consumption significantly contributes to environmental degradation and pollution [10–12].

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One promising solution is the production of binary blended cement, such as Type IP cement, which consists of 85% Portland cement and 15% pozzolanic material [13], thereby reducing reliance on Portland cement and its associated emissions [14]. Incorporating sustainable pozzolans, such as waste window glass and clay brick powder, introduces a novel technological pathway in cement production. Through pozzolanic reactions, these materials generate calcium silicate hydrates (C–S–H gel) that enhance the microstructure of ternary cement pastes by filling pores and refining the matrix [15, 16].

Waste clay bricks are abundant in many local construction sites. Their recycling into coarse or fine aggregates, or finely ground powders, has shown promising results in improving concrete quality [17–19]. In a study by Zhao et al. [20], increasing the grinding time of clay brick powder significantly enhanced its specific surface area and pozzolanic activity, resulting in finer particles within the blended cement paste. This particle size reduction accelerated early-age hydration and shortened setting time, as the ultrafine powder effectively serves as a nucleation site for hydration products. Moreover, mortars containing up to 30% clay brick powder exhibited a 10–35% increase in compressive strength compared to control mixtures without brick powder. These results confirm the accelerated strength development and performance benefits of using ultrafine recycled brick powder in sustainable cement formulations.

The incorporation of waste glass powder in concrete production has garnered considerable interest among researchers. For example, Shruthi [21] found that utilizing 15% glass powder enhanced strength properties due to its filler and pozzolanic effects. Similarly, Islam et al. [22] examined cement replacement with 0–25% glass powder, maintaining a constant ratio of cement and glass. Their results showed a 2% increase in compressive strength at 90 days for mixtures containing 20% glass powder, compared to a control mix.

Zakir et al. [23] evaluated the use of glass powder (≤75 microns) as a cement replacement at levels of 5%, 10%, 15%, 20%, 25%, and 30%, concluding that 20% replacement yielded the maximum improvement in both compressive (18%) and flexural strength (27%) at 28 days. In another study, Al-Zubaidi et al. [24] investigated the effects of using different sources of waste glass powder—green, neon, and brown glass—as partial cement replacements at 11%, 13%, and 15%. Among the variations tested, the use of 13% neon glass provided the greatest enhancement in both compressive and flexural strengths.

Recent advancements in concrete technology have also explored the application of high-fineness silica, particularly nano-silica, due to its exceptional ability to refine the microstructure and promote the formation of pozzolanic gels, resulting in high-performance concrete mixtures [25–30]. In line with this, the preparation and use of recycled nano glass-bottle powder as a cement substitute at replacement levels of 2.5%, 5%, 7.5%, and 10% demonstrated notable improvements. Specifically, a 5% replacement led to a 7.46% increase in flexural strength and an 11.49% increase in compressive strength at 28 days [31, 32]. These improvements are attributed to the high fineness and effective particle packing of nano-pozzolanic materials, which enhance the density and strength of the concrete matrix.

Finally, the reuse and recycling of waste materials not only improve the mechanical properties of concrete but also enhance its durability and permeability resistance by filling microstructural pores. These findings highlight the potential of sustainable blended cement as a promising area for further investigation and application in environmentally responsible construction [33, 34].

2. Experimental Methodology

The experimental program in this study was structured into two primary stages. In the first stage, high-fineness sustainable materials—namely clay brick (CB) and window glass (WG) powders—were prepared in accordance with the specifications of ASTM C618 [35]. These materials were then used to produce sustainable binary-blended cement following the guidelines of ASTM C595 [13], with the proposed nomenclature "SI" for this type of cement. To develop the binary-blended cement, ordinary Portland cement was partially replaced with CB and WG powders at 5%, 10%, and 15% by weight.

In the second stage, the sustainable cement developed in stage one was used to prepare concrete mixtures with low, medium, and high compressive strength levels, which were subsequently compared with a conventional control mix. The mix designs followed the recommendations of ACI PRC 211.1 [36], targeting compressive strengths of 2000 psi, 5000 psi, and 7000 psi, respectively.

Finally, the hardened properties of the concrete incorporating the sustainable Portland binary-blended cement were evaluated and benchmarked against those of the control mixtures. A detailed schematic of the entire methodology is illustrated in Figure 1.

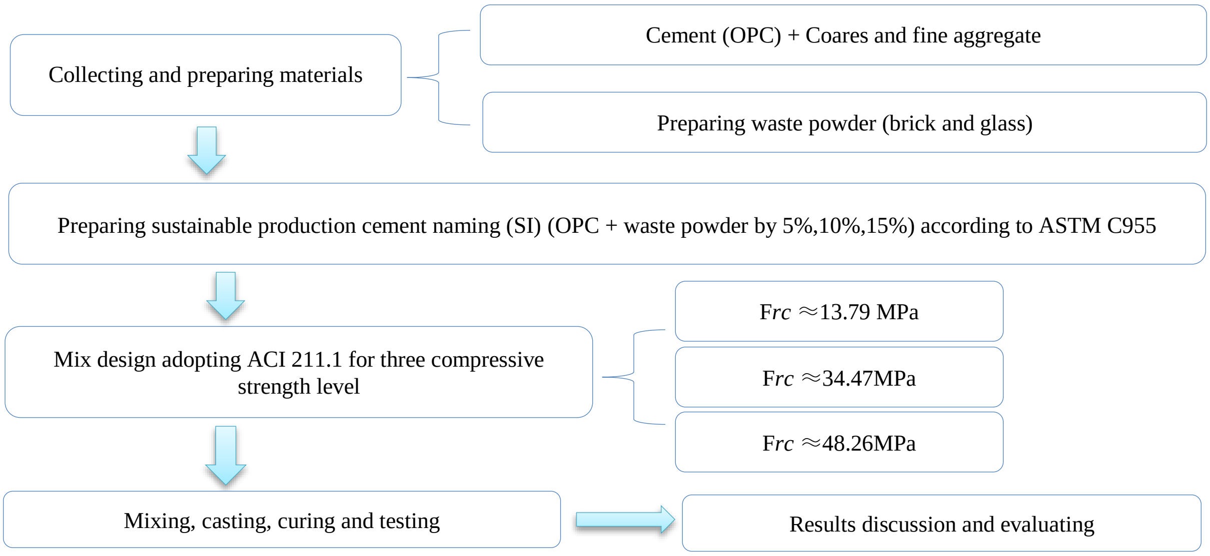


Figure 1. Flow-chart methodology investigation

2.1. Properties of Material

The normal early strength ordinary Portland [CEM I 42.5N] was used in this study. Table 1 presents the physical properties (setting time, soundness, surface Blaine area—cement fineness, and compressive strength), while Figure 2 displays the chemical composition of this type of cement. The tested results were identical to the Iraqi and American specification numbers 5 [37] and ASTM C150 [38]. The river fine aggregate (RFA) and crushed coarse aggregate (CCA) comply with the Iraqi Specification No. 45 [39] and ASTM C33/C33M-18 [40] that were used in this study. Table 2 presents the SO_3 % content and other physical properties, and Figure 3 demonstrates the sieving test of fine and coarse aggregate conforming to Iraqi specifications. Tap water was used for mixing and curing and confirmed to the Iraqi Specification No. 1703 [41].

Table 1. Cement properties

Property	Oxide-results (%)				Setting time Vicat (min)		Compressive Strength (MPa)				Surface Blaine area (m^2/kg)	C_3A (%)*	Soundness (%)
	MgO	SO_3	L.O.I.	I.R.	Initial	Final	2 days	28 days	3 days	7 days			
Results	3.22	2.24	1.60	0.45	110	308	18.5	43.2	15.2	23.5	285	8.60	0.12
IQS NO.5	≤ 5.0	≤ 2.8 if	≤ 4.0	≤ 1.50	≥ 45	≤ 600	≥ 10	≥ 42.5	-	-	≥ 260	-	≤ 0.8
ASTM C150	≤ 6.0	≤ 3.5 if	≤ 3.0	≤ 0.75	≥ 45	≤ 375	-	-	≥ 12	≥ 19	≥ 280	-	≤ 0.8

* Note: Calculated using bogue- equation from ASTM C 150.

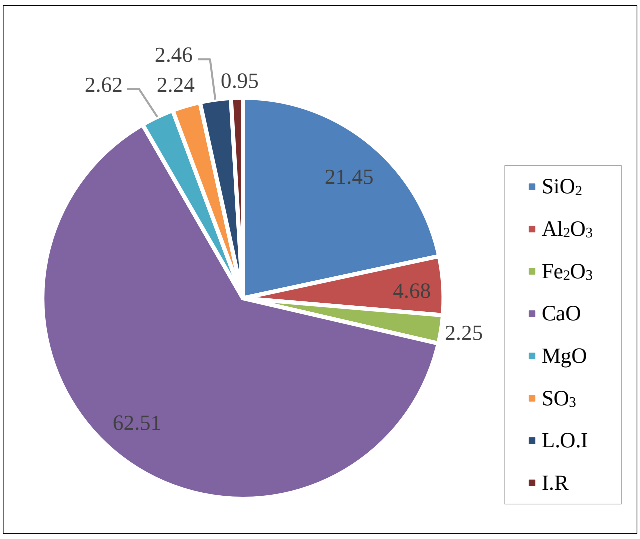


Figure 2. Chemical analysis of cement CEM I 42.5N

Table 2. Coarse and fine aggregate Properties

Properties	CC. A results	RF. A results
SO_3 (%) *	0.02	0.15
Specific gravity	2.61	2.59
Rodded density (kg/m^3)	1588	1720
Absorption (%)	0.62	0.85

* Note: Conforming IQS No. 45 (0.02 ≤ 0.1% and 0.15 ≤ 0.5%).

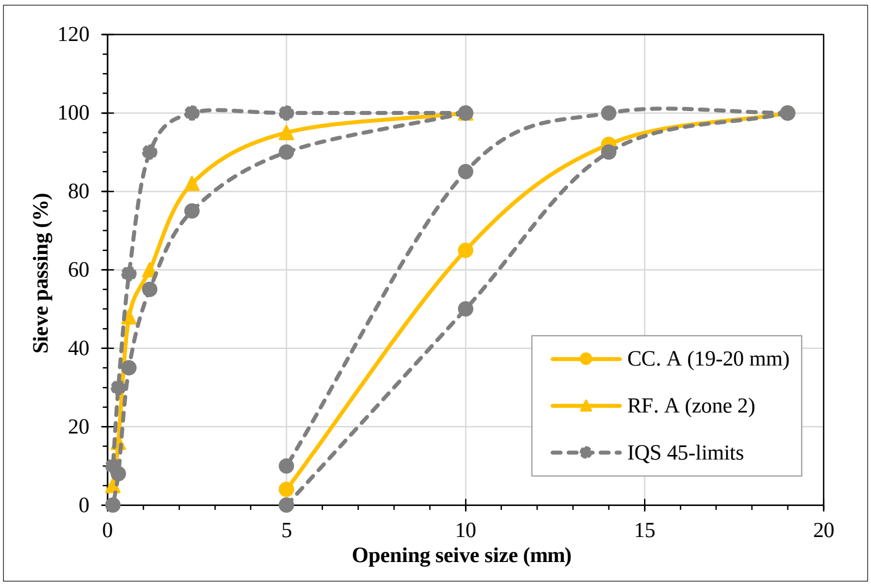


Figure 3. Sieving test for coarse and fine aggregate

On the other hand, the conversion process of waste materials—specifically clay brick (CB) and glass window (GW)—into recycled waste powder (RWP) is illustrated in Figure 4. Initially, the materials are manually pre-crushed using a hammer to a manageable size suitable for feeding into the crusher machine. The crushed material is then blended using a storming device to achieve finer particles. Finally, the powder is sieved to evaluate its particle size distribution and determine whether additional grinding is necessary. The physical and chemical properties of the resulting powders are summarized in Table 3, which assesses their suitability as high-fineness pozzolanic materials. The test results confirm compliance with the specifications outlined in ASTM C618 – Class N [35] and ASTM C595 – Type IP [13], validating their potential use in sustainable cement production.

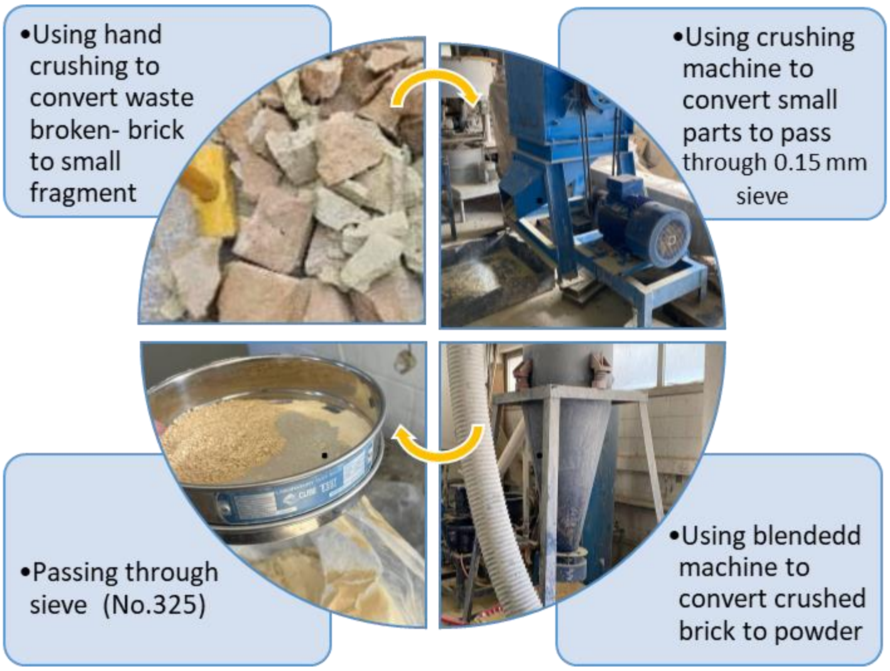


Figure 4. Process of converting waste brick to the powder

Table 3. Recycled waste powder properties

Properties		Results		Specification limits	
		GW	CB	ASTM C595	ASTM C618-N
Chemical analysis (%)	SiO_3	70.5	62.1	-	$[SiO_2 + Al_2O_3 + FE_2O_3] \geq 70$
	Al_2O_3	43.5	4.1		
	Fe_2O_3	7.5	12.2		
	SO_3	0.1	0.02	-	≤ 4
	L.O.I.	0.8	1.2	≤ 10	≤ 10
Activity- strength index at 28 days (%)		76.8	82.5	≥ 75	≥ 75
Wet passing- sieve 0.45 mm (%)		18	0	≤ 20	≤ 34

2.2. Mixing, Curing and Testing of Concrete-mixture

Figure 5 demonstrates the information of conventional concrete mix design of one cubic meter of concrete for low, medium, and high compressive strength (2000, 5000, and 7000 psi, respectively).

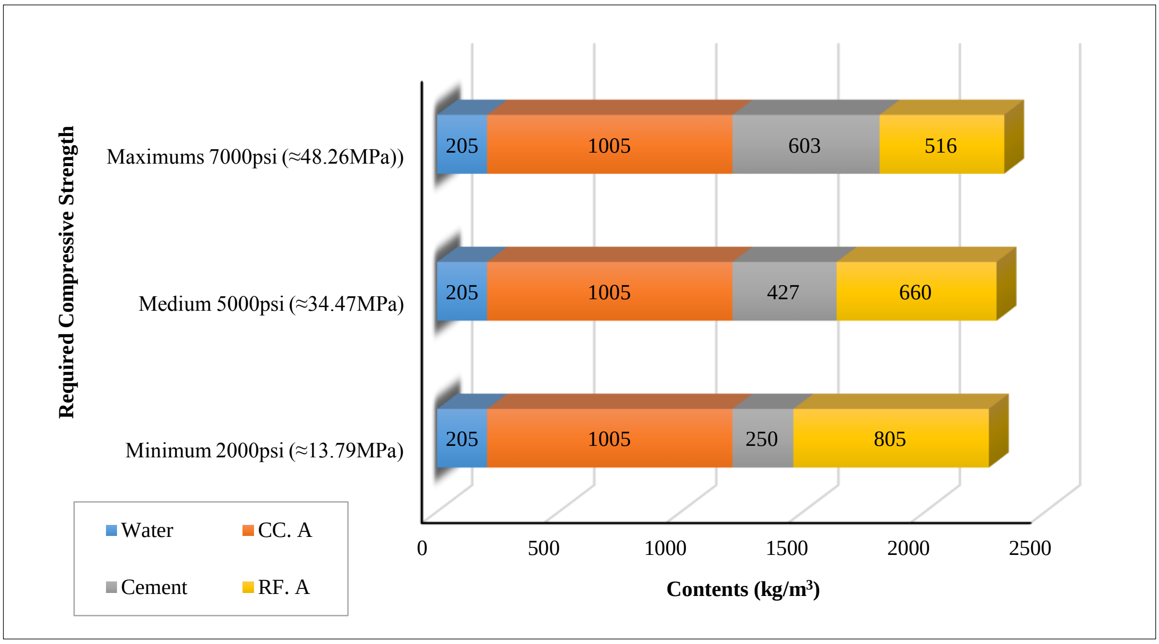


Figure 5. Mixture content adopting ACI PRC 211.1

The concrete mixing process was carried out in accordance with the specification ASTM C192 [42]. After that, the casting according to standard specification, then curing after casting of the standard specimens as shown in Figure 6. The details of casting of standard specimens and testing machine of compressive, flexural, and splitting tensile strength are tabulated in Table 4.

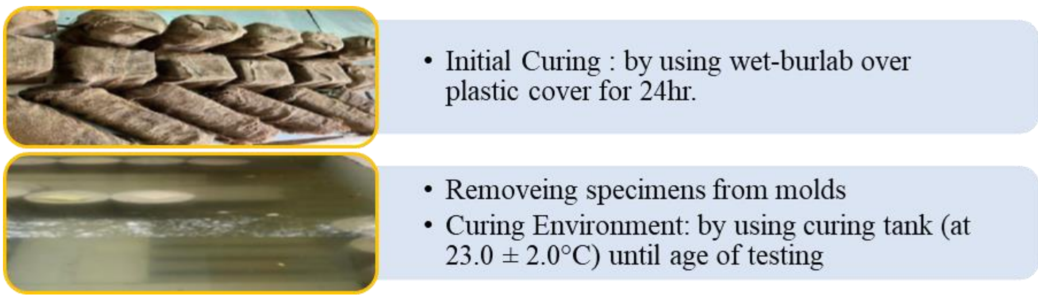


Figure 6. Curing regime according to ASTM C192

Table 4. Molds and testing details of concrete

Mold type and dimension (mm)	**Cube 100×100×100**	**Prism 100×100×400**	**Cylinder 150×300**
Casting specification	BS EN 12390-2 [43]	ASTM C192/C192M [42]	ASTM C192/C192M [42]
Strength test and specification	Compressive BS EN 12390-3 [44]	Flexural ASTM C293/C293M [45]	Splitting tensile ASTMC496/C496M [46]
Photo			

3. Results and Discussion

3.1. Sustainable Cement Production

The suggested sustainable production cement naming (IS) chemical composition conforms to ASTM C595 type IP [13] as presented in Table 5 and Figure 7. The using of brick or glass powder is encouraging, since the reduced amount of MgO, SO3 and L.O. I.

Table 5. Chemical analysis for IS cement and specification limits

Cement type	**SI-B5**	**SI-B10**	**SI-B15**	**SI-G5**	**SI-G10**	**SI-G15**	**ASTM C595 limits-IP**
MgO (%)	2.51	2.41	2.30	2.56	2.51	2.45	≤ 6
SO_3 (%)	2.13	2.02	1.91	2.13	2.03	1.92	≤ 4
L.O. I (%)	2.40	2.33	2.27	2.38	2.29	2.21	≤ 5

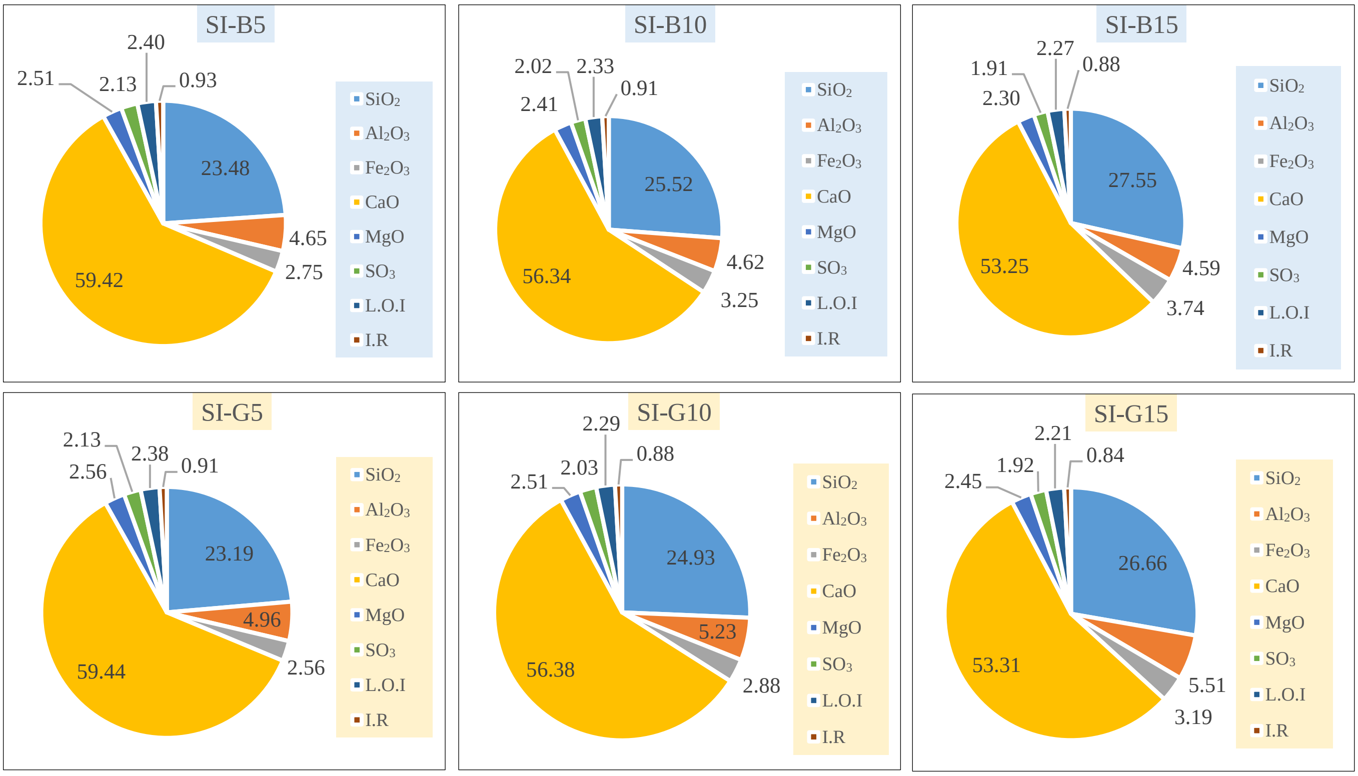


Figure 7. Sustainable binary-blended cement chemical analysis

Although the setting time increases with increasing powder of brick or glass percentage in sustainable cement, it still conforms to the blended cement limits as presented in Figure 8; the increase may be attributed to particle texture and its ability to bond and react with water. Finally, the main physical test, compressive strength results, also conforms to ASTM C595 type IP [13] as presented in Figure 9. The results showed that the brick powder can be adopted till 15% without compressive strength loss, also with glass powder with less improvement.

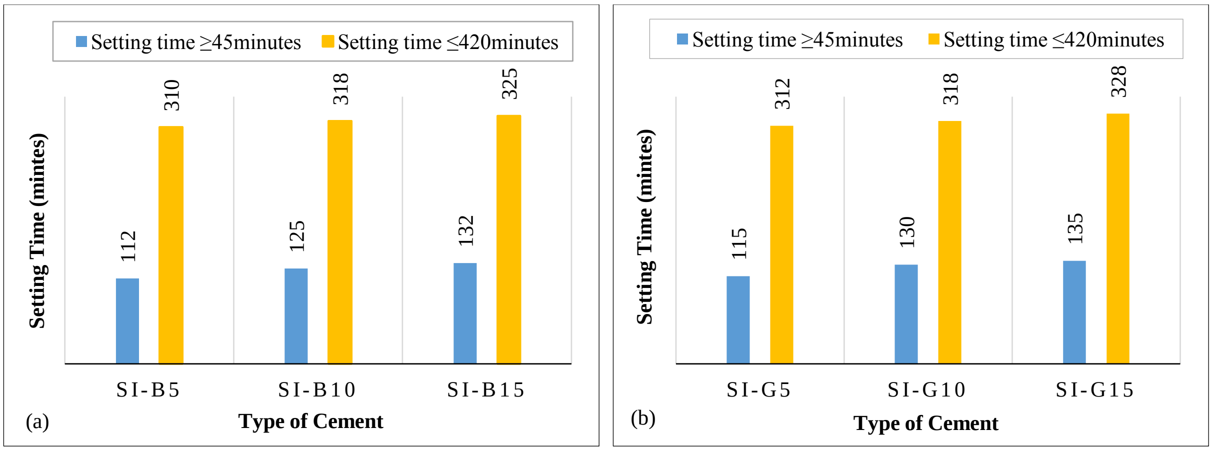


Figure 8. Setting time of manufactured sustainable binary-blended cement conforming to ASTM C595-IP limits, (a) for brick and (b) for glass

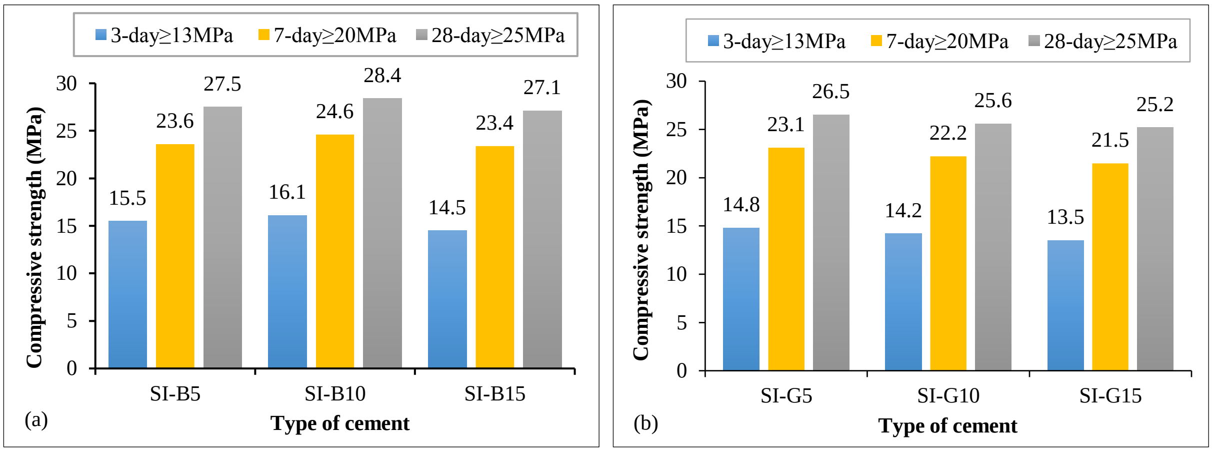


Figure 9. Compressive strength of manufactured sustainable binary-blended cement conforming to ASTM C595-IP limits, (a) for brick and (b) for glass

3.2. Evaluating Concrete Production Consuming Sustainable-Binary Cement

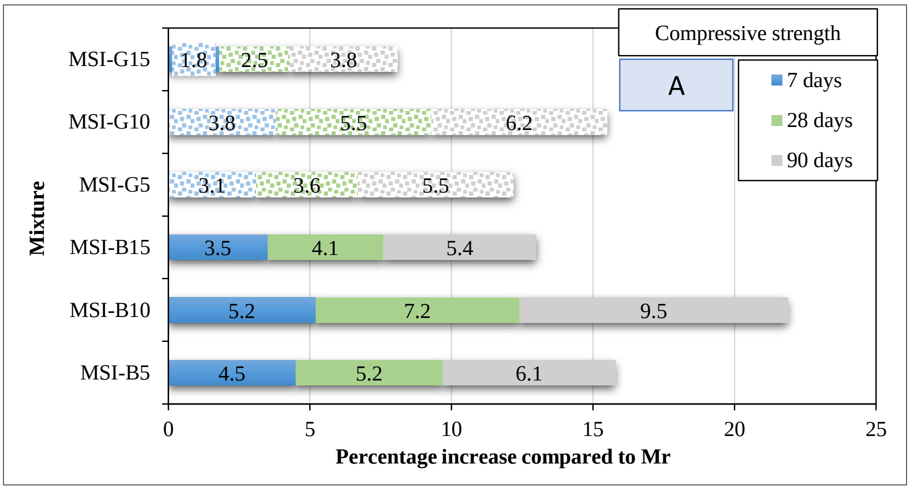
The development strength (compressive, flexural and splitting tensile) at 7, 28 and 90 days for reference mixture and other mixtures containing different sustainable manufactured cement (SI) presented in Table 6.

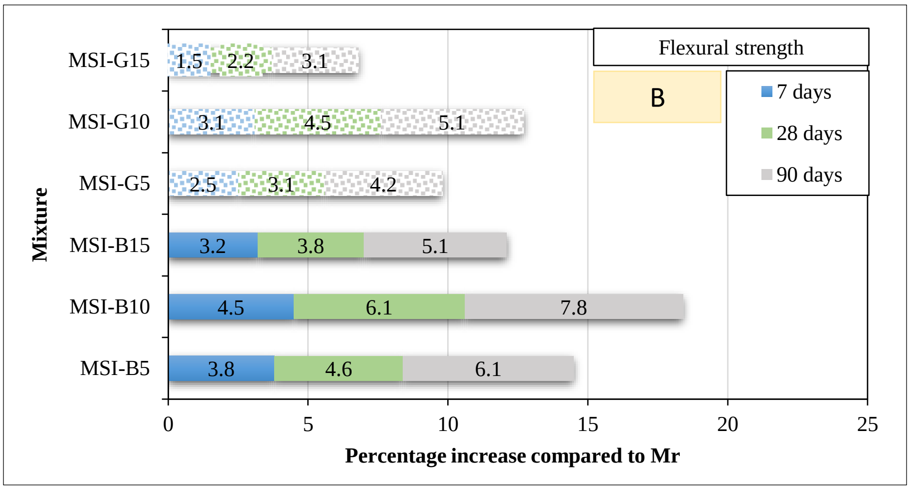
Table 6. Strength results

Strength	Age (days)	Mixture-Results for: F_{rc} ≈13.79 MPa						
		Mr	**MSI-B5**	**MSI-B10**	**MSI-B15**	**MSI-G5**	**MSI-G10**	**MSI-G15**
Compressive	7	11.41	11.92	12.00	11.81	11.76	11.84	11.62
	28	15.22	16.01	16.32	15.84	15.77	16.06	15.60
	90	16.80	17.82	18.40	17.71	17.72	17.84	17.44
Flexural	7	2.434	2.526	2.544	2.512	2.495	2.509	2.471
	28	3.121	3.265	3.311	3.240	3.218	3.261	3.190
	90	3.433	3.642	3.701	3.608	3.577	3.608	3.539
Splitting tensile	7	1.612	1.678	1.683	1.668	1.651	1.657	1.638
	28	2.025	2.122	2.136	2.110	2.090	2.096	2.070
	90	2.274	2.406	2.460	2.383	2.367	2.390	2.358
Mixture-Results for: F_{rc} ≈34.47 MPa								
Compressive	7	28.52	30.40	30.72	30.19	30.00	30.15	29.69
	28	36.25	38.90	39.77	38.59	38.32	38.50	37.99
	90	39.52	42.76	44.26	42.58	42.52	42.72	41.93
Flexural	7	3.025	3.203	3.237	3.19	3.16	3.18	3.14
	28	3.855	4.113	4.187	4.09	4.06	4.07	4.03
	90	4.235	4.582	4.671	4.55	4.50	4.52	4.46

Splitting tensile	7	2.45	2.602	2.619	2.59	2.56	2.57	2.55
	28	3.185	3.405	3.440	3.39	3.35	3.37	3.33
	90	3.515	3.793	3.891	3.77	3.73	3.75	3.73
Mixture-Results for: F_{rc} ≈48.26 MPa								
Compressive	7	38.8	41.1	41.7	40.9	40.5	41.2	40.1
	28	50.3	53.6	55.0	53.2	52.7	54.1	52.3
	90	54.5	58.6	60.9	58.5	58.2	59.1	57.4
Flexural	7	4.426	4.658	4.725	4.650	4.592	4.661	4.561
	28	5.675	6.018	6.149	5.996	5.922	6.056	5.888
	90	6.125	6.587	6.741	6.551	6.459	6.573	6.410
Splitting tensile	7	4.064	4.290	4.334	4.281	4.212	4.268	4.192
	28	5.216	5.542	5.620	5.532	5.448	5.514	5.412
	90	5.735	6.151	6.334	6.116	6.042	6.155	6.037

The cumulative percentage improvement in low-level compressive strength across all curing ages was recorded as 15.8%, 21.9%, and 13% for brick powder (BP), and 12.2%, 15.5%, and 8.1% for glass powder (GP), corresponding to 5%, 10%, and 15% replacement levels of cement, respectively, as illustrated in Figure 10-a. A similar trend was observed for flexural and splitting tensile strengths, with cumulative improvements of 14.6%, 18.3%, and 12.3% ±0.2 for BP and 9.8%, 12.5%, and 6.8% ±0.2 for GP at the same replacement levels, as shown in Figures 10-b and 10-c. These enhancements in mechanical performance are attributed to the pozzolanic reactions and microstructural densification resulting from the high fineness of the powders, which effectively fill voids within the cement matrix. The findings support the safe and effective use of sustainable cement incorporating brick or glass powder, particularly at the 10% replacement level, due to their high strength activity index and optimal fineness [21, 22, 31, 47]. Moreover, brick powder demonstrates stronger pozzolanic reactivity, likely due to its textural properties and interaction behavior within the concrete matrix [48]. The incorporation of such high-fineness materials significantly enhances packing density, promotes hydration, and improves bonding between concrete components, ultimately contributing to a dense microstructure and improved durability [49, 50].





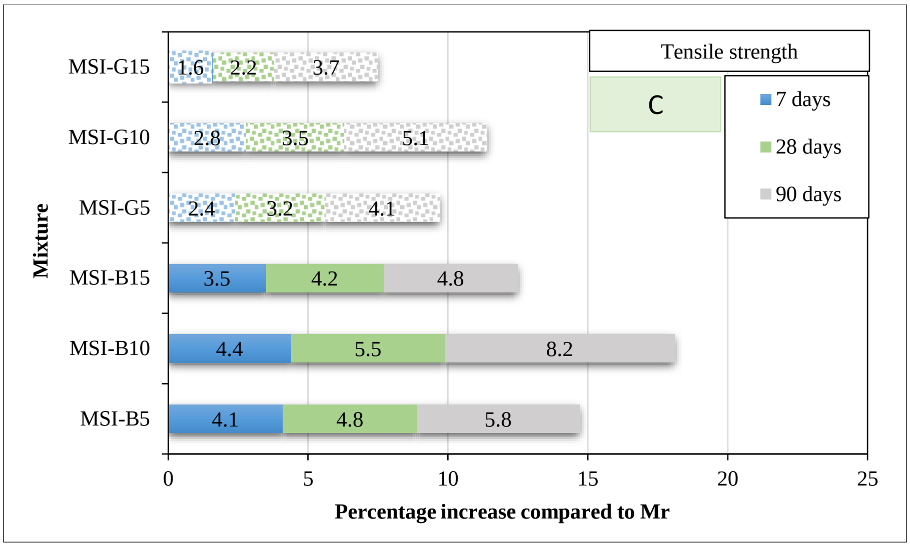
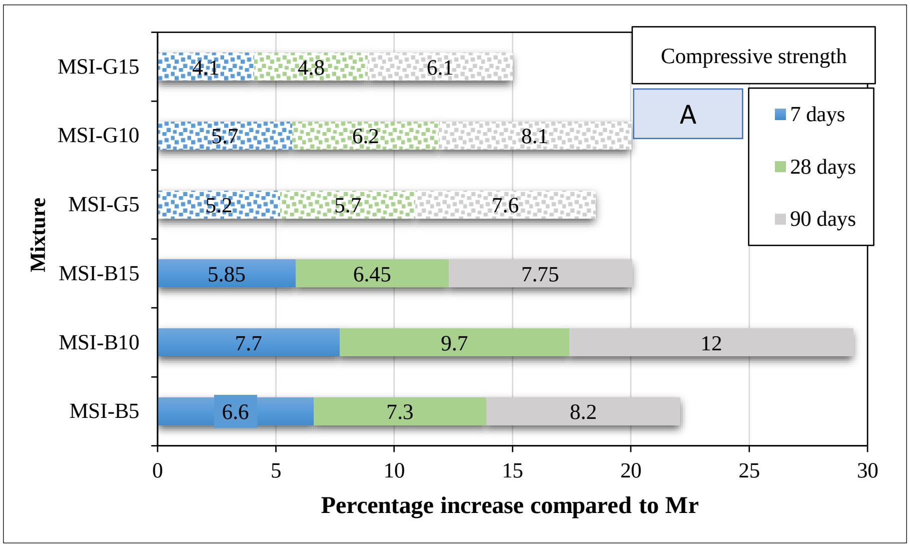
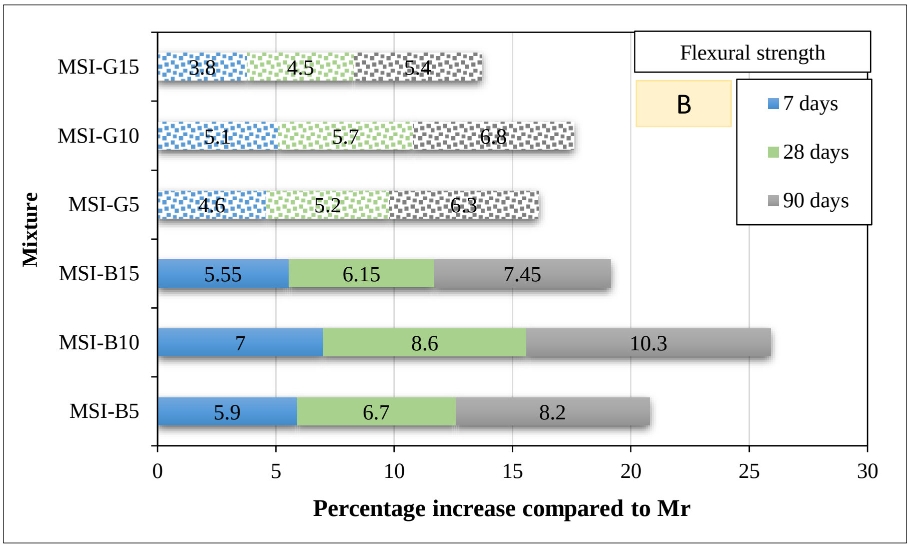


Figure 10. Copulative percentage improvement for low-level compressive strength

The development strength for medium- and high-level strength is presented in Figures 11 and 12, respectively, the results also supporting using sustainable binary cement safely. Figure 13 presents a high correlation between compressive, flexural, and splitting strength.





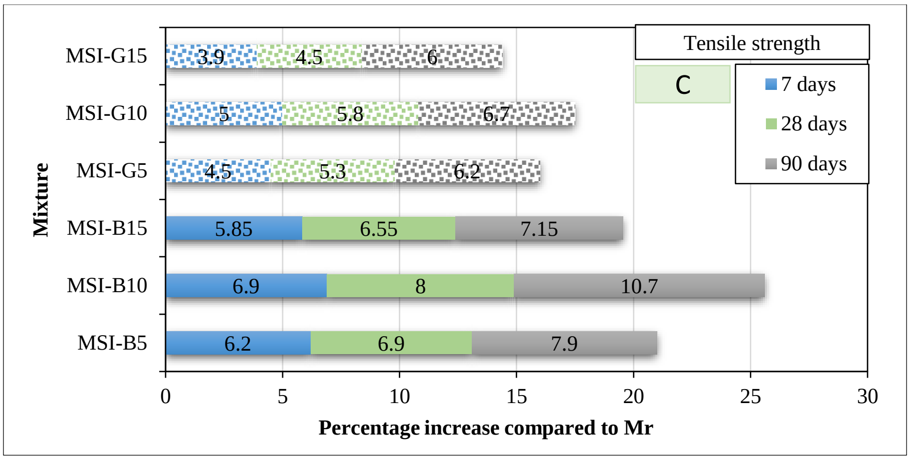


Figure 11. Copulative percentage improvement for medium-level compressive strength

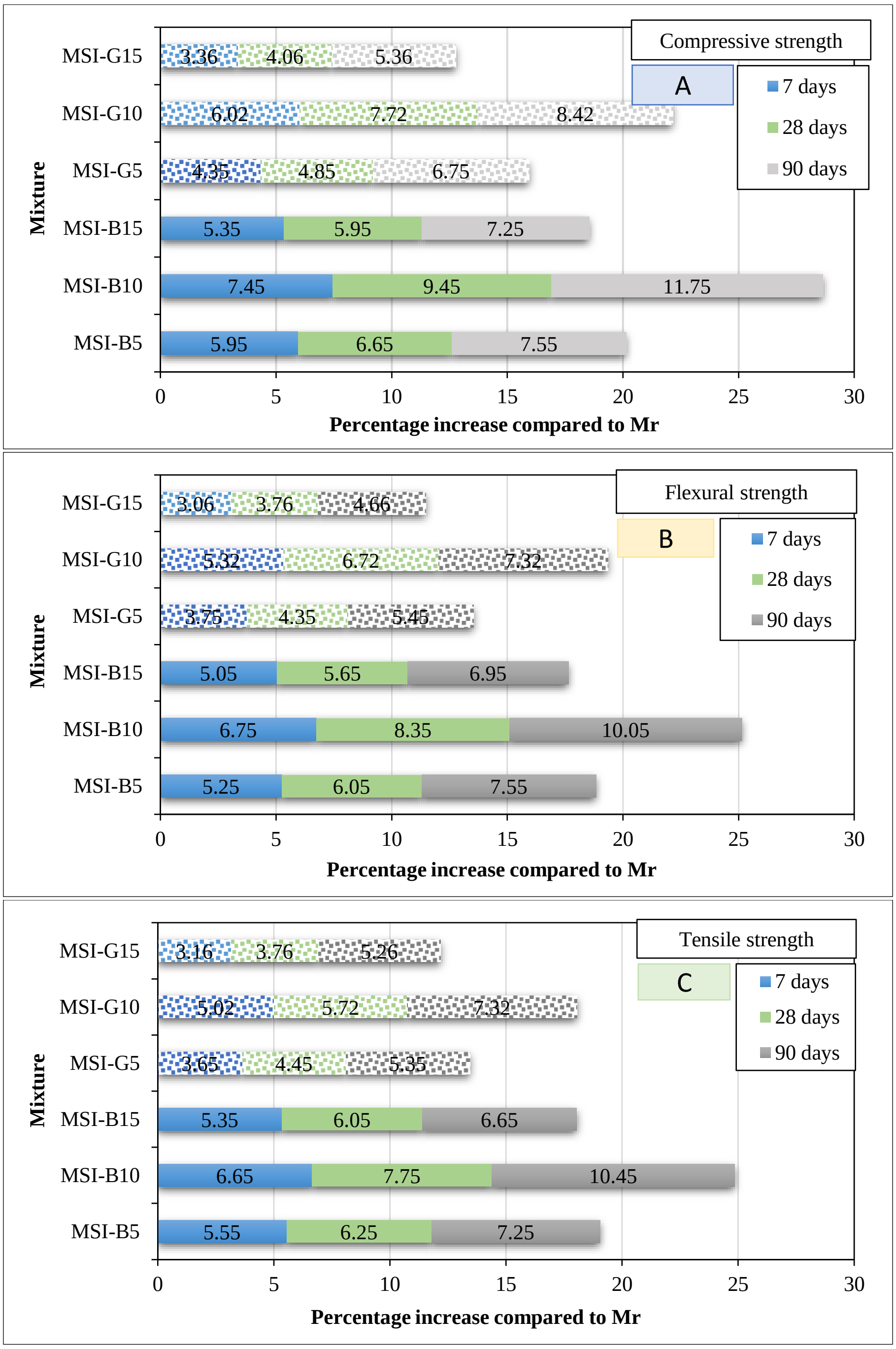


Figure 12. Copulative percentage improvement for high-level compressive strength

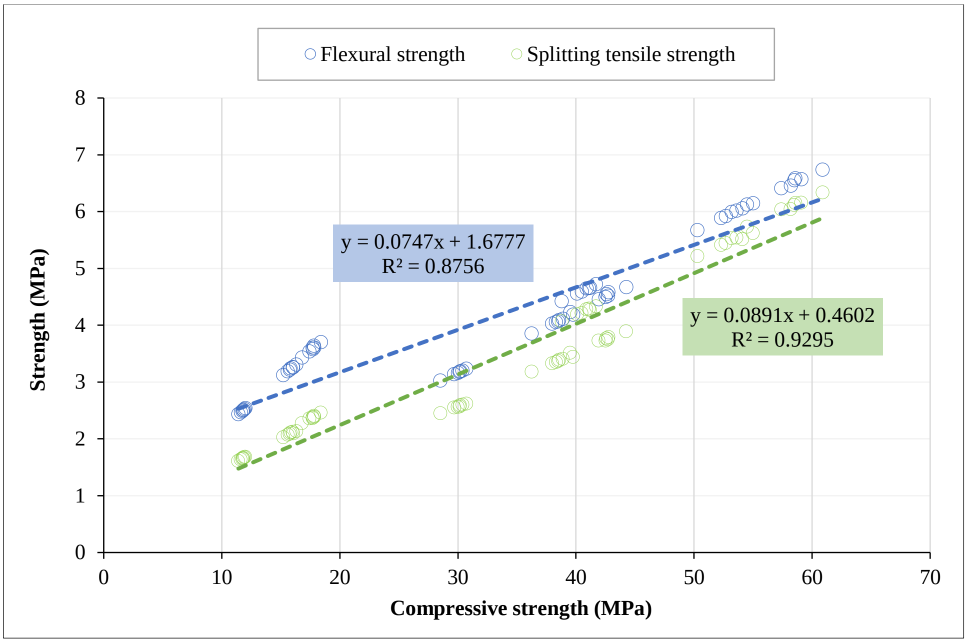


Figure 13. An example of a figure

4. Conclusions

- The successful fabrication of sustainable binary cement in accordance with ASTM C595, with the designated label "SI", represents a significant achievement in sustainable materials development.
- Replacing up to 15% of ordinary Portland cement with yellow clay-brick or window glass powder is feasible and meets the chemical and physical specifications outlined in ASTM C595.
- The study highlights a notable increase in setting time for cement containing 5%, 10%, and 15% brick or glass powder replacements, all remaining within acceptable specification limits.
- The produced sustainable cement demonstrated enhanced compressive strength at 3, 7, and 28 days when compared to conventional OPC.
- The cumulative improvement in low-strength concrete compressive strength reached 15.8%, 21.9%, and 13% for MSI-B5, MSI-B10, and MSI-B15, and 12.2%, 15.5%, and 8.1% for MSI-G5, MSI-G10, and MSI-G15, respectively.
- For medium-strength concrete, compressive strength increased by 22.1%, 29.4%, and 20.05% for MSI-B5, MSI-B10, and MSI-B15, and by 18.5%, 20%, and 15% for MSI-G5, MSI-G10, and MSI-G15, respectively.
- In high-strength concrete, improvements were recorded at 20.15%, 28.65%, and 18.55% for MSI-B5, MSI-B10, and MSI-B15, and 15.95%, 22.16%, and 12.78% for MSI-G5, MSI-G10, and MSI-G15, respectively.
- Among the evaluated mixes, SI-B10 and SI-G10—containing 10% brick or glass powder, respectively—demonstrated the most effective enhancement in strength across all strength levels and are thus recommended for optimal performance.
- Improvements in flexural and splitting tensile strength were also observed, showing a strong correlation with compressive strength, confirming the viability of sustainable binary cement across different strength classes.

5. Declarations

5.1. Author Contributions

Conceptualization, H.A.A., Z.K.A., R.S.M., and A.A.A.; methodology, H.A.A., Z.K.A., R.S.M., and A.A.A.; software, H.A.A., Z.K.A., and R.S.M.; validation, H.A.A., Z.K.A., R.S.M., and A.A.A.; formal analysis, H.A.A., Z.K.A. and R.S.M.; investigation, H.A.A., Z.K.A., and R.S.M.; resources, H.A.A., Z.K.A., and R.S.M.; data curation, H.A.A. and Z.K.A.; writing—original draft preparation, H.A.A. and Z.K.A.; writing—review and editing, H.A.A., Z.K.A., R.S.M., and A.A.A.; visualization, H.A.A., Z.K.A., and R.S.M.; supervision, H.A.A. and Z.K.A.; project administration, H.A.A. and Z.K.A.; funding acquisition, H.A.A., Z.K.A., and R.S.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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