

Development of Green Concrete incorporating Recycled Glass Powder for Sustainable Construction and Material Conservation

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ABSTRACT

This study explores the innovative reuse of recycled glass powder (GP) as a sustainable partial substitute for fine aggregates in concrete production. In line with research on Supplementary Cementitious Materials (SCM) and Malaysia's carbon-neutrality aspirations, the study aims to reduce both environmental impact and reliance on raw materials. Aimed at reducing both environmental impact and reliance on raw materials in construction, M30 grade concrete mixes were designed using the Department of Environment (DOE) method with 0%, 5%, 10%, and 15% GP incorporation. Twenty-four cube specimens were cast and tested for key performance indicators: workability, compressive strength, ultrasonic pulse velocity (UPV), and water absorption. Results revealed that mixes with 0%–5% GP achieved enhanced workability (28–36% increase) and reduced water absorption (by 1.54–1.67%), suggesting better fresh and durability properties. Meanwhile, 10%–15% GP mixes excelled in mechanical performance, with UPV improving by 4.7–5.7% and compressive strength rising by 5.7–20.9% (1.8–7.5 MPa). These findings confirm that GP, when optimally dosed, enhances both the fresh and hardened properties of concrete, promoting its use as a high-performance, eco-friendly material in sustainable construction. This study provides practical insights into green concrete design strategies that align with circular-economy goals and resource-conservation efforts.

Keywords: Mechanical and durability performance, Recycled glass powder, Supplementary cementitious materials, Sustainable concrete.

1. INTRODUCTION

The global construction sector is witnessing increasing demand for sustainable, environmentally responsible practices, particularly in the use of concrete, the most widely used building material worldwide. Traditionally composed of cement, water, coarse aggregate, and fine aggregate, concrete plays a pivotal role in infrastructure development worldwide. However, its production contributes significantly to environmental degradation due to the heavy reliance on non-renewable resources such as sand, aggregates, and energy sources [1]. In response to escalating environmental concerns, researchers have focused on integrating waste materials into concrete mixtures, transforming industrial and domestic by-products into functional components of modern construction. Previous studies have integrated various SCMs, including fly ash, palm oil fuel ash (POFA), and silica fume. However, Malaysian adoption remains limited due to cost, lack of incentives, and low stakeholder readiness. Compared to countries such as Japan and the EU,

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where recycled glass aggregates achieve wider acceptance, Malaysia still lags in both feasibility studies and implementation. This study builds on international findings while contextualizing glass powder's potential for Malaysia by focusing on feasibility, performance, and adoption barriers.

Among these waste materials, glass waste has emerged as a promising substitute for fine aggregates. Vast quantities of discarded glass from households, commercial industries, and construction sites present a critical environmental issue, as glass is non-biodegradable and accumulates in landfills over time, leading to land pollution and increasing disposal costs [2]. The transformation of such waste into recycled glass powder (GP) offers an eco-friendly and economically viable approach to concrete production. This powder, when processed to a fine size, can be effectively utilized to enhance various properties of concrete, including workability, strength, and durability.

Glass is an amorphous solid formed through the rapid cooling of molten raw materials such as silica, soda ash, and calcium carbonate (CaCO_3). While naturally occurring in rare conditions, most glass used today is synthetically produced and is known for its recyclability. Recycling glass not only conserves raw materials and energy but also reduces the carbon footprint of construction operations. Previous studies have demonstrated that glass powder, when incorporated in optimal proportions, can significantly improve the performance of concrete mixtures [3]. For Marine Application, Chloride penetration tests [20] show that 15% GP concrete achieves >50% reduction vs. the control, critical for coastal structures [4].

Nevertheless, one of the primary challenges in using waste glass in concrete is the risk of alkali-silica reaction (ASR), a chemical reaction between the reactive silica in glass and the alkalis in cement. This reaction can lead to expansion, cracking, and deterioration over time, posing structural concerns for long-term durability [5]. Therefore, comprehensive experimental investigations are essential to validate the safe integration of glass powder in concrete and to determine its optimal usage in structural applications.

2. MATERIAL AND METHODS

The objective of this study is to evaluate the performance of green concrete produced by partially replacing fine aggregates with recycled glass powder (GP). The study specifically investigates the physical and mechanical characteristics of M30 grade concrete incorporating varying percentages of GP. The experimental program involved a series of standard tests, including workability, compressive strength, ultrasonic pulse velocity (UPV), and water absorption, conducted on concrete samples prepared with controlled mix proportions.

2.1 Materials

This study used ASTM Type I Ordinary Portland Cement (Grade M30) as the main binder due to its established performance in Malaysian infrastructure and favourable mechanical properties. M30 cement has been shown to exhibit superior compressive and tensile strengths compared to other grades, making it a suitable choice for developing green concrete mixes [1]. The cement was stored in sealed containers under controlled conditions ($\leq 60\%$ relative humidity) to prevent premature hydration prior to usage.

Coarse aggregate with a maximum nominal size of 20 mm was selected and subjected to detailed sieve analysis in accordance with ASTM C136M-14. The material was found to meet the particle size distribution limits specified in ASTM C33M-16. The same standard was followed for the characterization of fine aggregate, which consisted of natural river sand, ensuring compliance with grading and purity requirements under ASTM C33/C33M-16.

The recycled glass powder (GP), utilized as a sustainable fine aggregate replacement, was obtained from Tung Yung Glass Aluminium Sdn. Bhd., located in Kangar, Malaysia. The glass waste underwent controlled crushing and sieving to produce a powder with a maximum particle size of 75 μm , as verified by laser diffraction particle size analysis. X-ray fluorescence (XRF) spectroscopy revealed that the GP consisted mainly of silica (72–75%), sodium oxide (12–14%), and calcium oxide (8–10%).

Potable water was used for mixing and curing throughout the experiment. The water complied with WHO drinking water standards and was regularly tested to ensure it remained free of impurities that could adversely affect cement hydration or concrete durability. The pH was maintained within the recommended range of 6.5 to 7.5 to ensure chemical stability during mixing and curing.



Figure 1: Binding Material used for Mixing Proportion.

2.2 Mix Design and Specimen

The concrete mix design in this study was developed to achieve M30 grade strength using the Department of Environment (DOE) method. Four concrete mix variations were formulated, incorporating recycled glass powder (GP) at 0% (control), 5%, 10%, and 15% as a partial replacement by weight of fine aggregates. The control mix adopted an optimized ratio of 1:1.94:3.43 for cement, fine aggregate, and coarse aggregate, respectively. A constant water-to-cement (w/c) ratio of 0.54 was maintained throughout all mixes, as determined through preliminary trials to ensure satisfactory workability and strength performance.

All mix proportions included an additional 10% material allowance to account for expected losses during batching and handling. Mixing was performed using a laboratory pan mixer at 28 rpm for 5 minutes to ensure uniform dispersion of all constituents. The detailed mix proportions are provided in Table 1, while the procedural flow of the DOE method is illustrated in Figure 2.

Stage	Item	Reference or calculation	Value		
1	1.1	Characteristic strength	Specified — $\left[\frac{30}{\text{Proportion defective}} \right]$ N/mm ² at $\frac{28}{5}$ days per cent		
	1.2	Standard deviation (σ)	Fig 3 $\frac{8}{\text{N/mm}^2}$ or no data $\frac{\text{N/mm}^2}{\text{N/mm}^2}$		
	1.3	Margin ($k \times \sigma$)	C1 $(k = 1.64) \frac{1.64 \times 8}{\text{N/mm}^2} = \frac{13.12}{\text{N/mm}^2}$		
	1.4	Target mean strength	C2 $\frac{30}{\text{N/mm}^2} + \frac{13}{\text{N/mm}^2} = \frac{43}{\text{N/mm}^2}$		
	1.5	Cement type	Specified OPC SRP / RHPC		
	1.6	Aggregate type : coarse	crushed		
	1.6	Aggregate type : fine	uncrushed		
	1.7	free-water / cement ratio	Table 2, Fig 4 $\frac{0.54}{\text{N/mm}^2}$	Use the lower value 0.54	
1.8	Maximum free-water / cement ratio	Specified $\frac{0.65}{\text{N/mm}^2}$			
2	2.1	Slump or V-B	Specified Slump $\frac{30-60}{\text{mm}}$ or V-B $\frac{3-6}{\text{s}}$		
	2.2	Maximum aggregate size	Specified $\frac{20}{\text{mm}}$		
	2.3	Free - water content	Table 3 $\frac{190}{\text{kg/m}^3}$		
3	3.1	Cement content	C3 $\frac{190}{\text{kg/m}^3} \div \frac{0.54}{\text{N/mm}^2} = \frac{352}{\text{kg/m}^3}$		
	3.2	Maximum cement content	Specified $\frac{-}{\text{kg/m}^3}$		
	3.3	Minimum cement content	Specified $\frac{-}{\text{kg/m}^3}$ - Use if greater than Item 3.1 and calculate Item 3.4		
	3.4	Modified free-water /cement ratio	$\frac{352}{\text{kg/m}^3}$		
4	4.1	Relative density of aggregate (SSD)	$\frac{2.7}{\text{known/ assumed}}$		
	4.2	Concrete density	Fig 5 $\frac{2430}{\text{kg/m}^3}$		
	4.3	Total aggregate content	C4 $\frac{2430}{\text{kg/m}^3} - \frac{190}{\text{kg/m}^3} - \frac{352}{\text{kg/m}^3} = \frac{1888}{\text{kg/m}^3}$		
5	5.1	Grading of fine aggregate	BS 882 Zone $\frac{50}{\text{per cent}}$		
	5.2	Proportion of fine aggregate	Fig 6 $\frac{36}{\text{per cent}}$		
	5.3	Fine aggregate content	C5 $\left[\frac{0.36}{\text{kg/m}^3} \times \frac{1888}{\text{kg/m}^3} = \frac{680}{\text{kg/m}^3} \right]$		
	5.4	Coarse aggregate content		$\frac{1888}{\text{kg/m}^3} - \frac{680}{\text{kg/m}^3} = \frac{1208}{\text{kg/m}^3}$	
Quantities		Cement (kg)	Water (kg or l)	Fine aggregate (kg)	Coarse aggregate (kg)
per m ³ (to nearest 5 kg)		$\frac{352}{\text{kg}}$	$\frac{190}{\text{kg}}$	$\frac{680}{\text{kg}}$	$\frac{1208}{\text{kg}}$
per trial mix of 0.003 m ³		$\frac{1}{\text{kg}}$	$\frac{0.54}{\text{kg}}$	$\frac{1.93}{\text{kg}}$	$\frac{3.43}{\text{kg}}$

Item in italics are optional limiting values that may be specified (see Section 7)
 1 N/ mm2 = 1 MN/ m = 1 MPa (see footnote on page 8)
 OPC = ordinary Portland cement; SPRC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement
 Relative density = specific gravity (see footnote on page 15)
 SSD = based on a saturated surface-dry basis

Figure 2: DOE method detailing.

Table 1: Quantities and proportions of mixing materials for 0.54 w/b ratio concrete mixes.

Concrete Type	Glass Powder (%)	Cement (kg/m ³)	Water (kg/m ³)	Fine aggregate (kg/m ³)	Glass Powder (kg/m ³)	Coarse Aggregate (kg/m ³)
Control	0	1.16	0.63	2.24	0	3.99
GP5	5	1.16	0.63	2.12	0.12	3.99
GP10	10	1.16	0.63	2.02	0.23	3.99
GP15	15	1.16	0.63	1.9	0.34	3.99

2.3 Samples Preparation

Fresh concrete workability was evaluated using the standard slump test. A steel slump cone (300 mm height, 200 mm base diameter, 100 mm top diameter) was used on a rigid, non-absorbent base. The cone was lubricated with oil before each test to avoid adhesion. Only mixes showing true slump behavior, defined by uniform settlement without collapse or shear, were accepted. Any mix that exhibited inconsistent slump results was rejected and remixed.

The approved mixes were cast into 100 mm × 100 mm × 100 mm steel cube moulds pre-treated with a form-release agent. The concrete was placed in four layers, each compacted with 25 strokes of a 16 mm diameter tamping rod to minimize voids and ensure proper compaction. After finishing with a steel trowel, the specimens were covered with moist burlap and left to set for 24 ± 2 hours before demolding. Demolded samples were submerged in a water-curing tank maintained at 20 ± 2°C and 95 ± 5% relative humidity. The specimens were cured for 7 and 28 days to facilitate adequate hydration and strength development before mechanical testing.

3. RESULTS AND DISCUSSION

The performance of concrete mixes incorporating varying percentages of glass powder (GP) as a partial replacement for fine aggregate was evaluated through a series of tests on workability, water absorption, ultrasonic pulse velocity (UPV), and compressive strength. The findings demonstrate that GP inclusion significantly influences the physical and mechanical behaviour of concrete, depending on its replacement level.

3.1 Slump Test

The slump test results indicated a consistent increase in workability with higher GP content, as shown in Figure 3. The control mix (0% GP) exhibited a slump of 46 mm, while GP5, GP10, and GP15 recorded slump values of 64 mm, 72 mm, and 87 mm, respectively. The 15% GP mix achieved an 89% increase in slump compared to the control, notably exceeding the 35% improvement reported by Arivalagan et al. [6].

This enhancement is attributed to the spherical morphology of the fine glass particles ($\leq 75 \mu\text{m}$), which act as micro-ball bearings, reducing internal friction and increasing flowability. Additionally, GP's lower water demand compared to cement frees more water for lubrication, enhancing workability without segregation. These characteristics make higher GP content suitable for applications such as pumped concrete and detailed formworks. However, further consideration is needed regarding its effect on early-age strength.

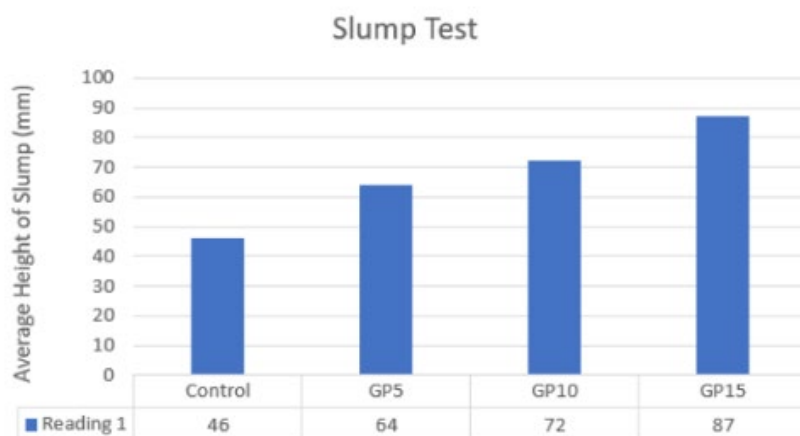


Figure 3: Average slump height for GP-modified concrete mixes.

3.2 Water Absorption Test

Water absorption results, summarized in Figure 4, showed a downward trend with increasing GP content. The absorption rate decreased from 1.90% (control) to 1.44% at 15% GP, indicating a 24% improvement in impermeability. This aligns with findings by K.I.M. Ibrahim [7] and suggests that GP enhances concrete durability by refining pore structure. The reduction is linked to the fine particle packing and pozzolanic reactivity of GP, which fill voids and form additional C-S-H gel, thereby densifying the concrete matrix. Interestingly, the 15% GP mix displayed the lowest absorption despite having the highest glass content, supporting the hypothesis that this Proportion optimally balances filler efficiency without causing particle clustering.

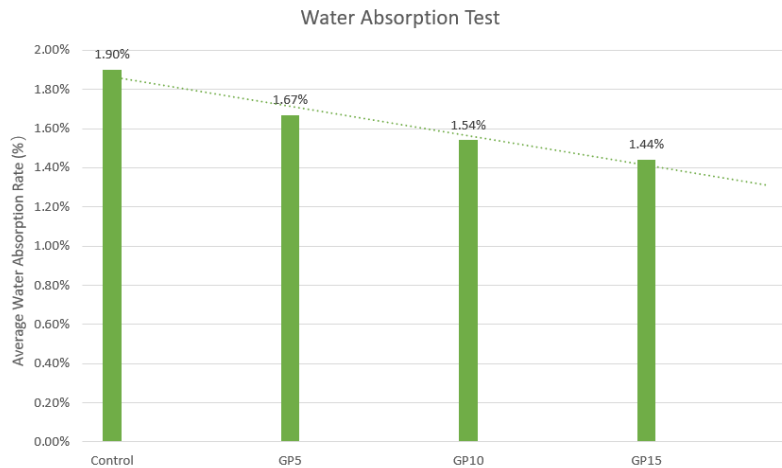


Figure 4: Average water absorption results for GP-modified concrete.

3.3 Compressive Test

The compressive strength test results are presented in Figure 5. At 7 days, a gradual increase in strength was observed across all mixes, with the highest strength at 15% GP. At 28 days, the control mix was outperformed by all GP mixes except GP5, which showed a slight initial dip in strength. The 15% GP mix achieved a 21% increase in 28-day compressive strength, exceeding the 19% gain reported by K.I.M. Ibrahim [7]. The improvement is attributed to two synergistic mechanisms: the pozzolanic reaction between GP and calcium hydroxide, forming additional C-S-H gel, and the micro-filling action of GP, which reduces porosity by 12–18%.

The slight reduction in strength at 5% GP likely resulted from incomplete dispersion and localized clustering. As GP content increased, particle distribution became more uniform, resulting in higher strength and denser matrices. The compressive strength of 35.87 MPa at 15% GP meets the ACI 318-22 [9] requirement for Class M30 concrete and demonstrates better thermal stability at elevated temperatures, suggesting that an optimized GP content enhances structural performance while supporting sustainability objectives.

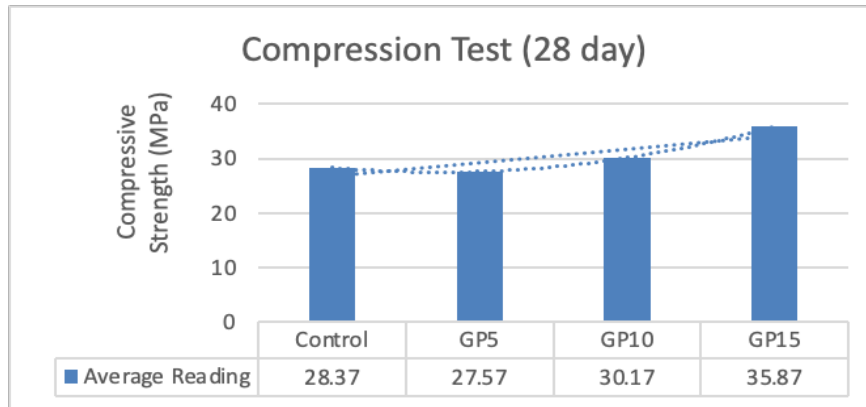


Figure 5: 28-day compressive strength for GP concrete mixes.

3.4 Physical Properties

Concrete incorporating 0%–5% GP demonstrated the most advantageous physical performance. As illustrated in Figure 6, these mixtures achieved improved workability, with slump values ranging between 64 mm and 72 mm, representing a 28–36% increase compared to the control mix. In parallel, water absorption was significantly reduced, ranging from 1.54% to 1.67%, confirming enhanced resistance to moisture ingress. These improvements are largely attributed to the efficient particle packing and lubricating effect of the finely ground glass particles, which help reduce internal friction and fill voids in the matrix. Furthermore, the relatively low GP content prevents agglomeration and preserves matrix homogeneity, as supported by ultrasonic pulse velocity results that showed more consistent wave transmission in these samples. Consequently, concrete with up to 5% GP content is highly favorable for applications requiring accurate placement, good surface finish, and enhanced weather resistance, such as thin-shell structures or architectural concrete elements.

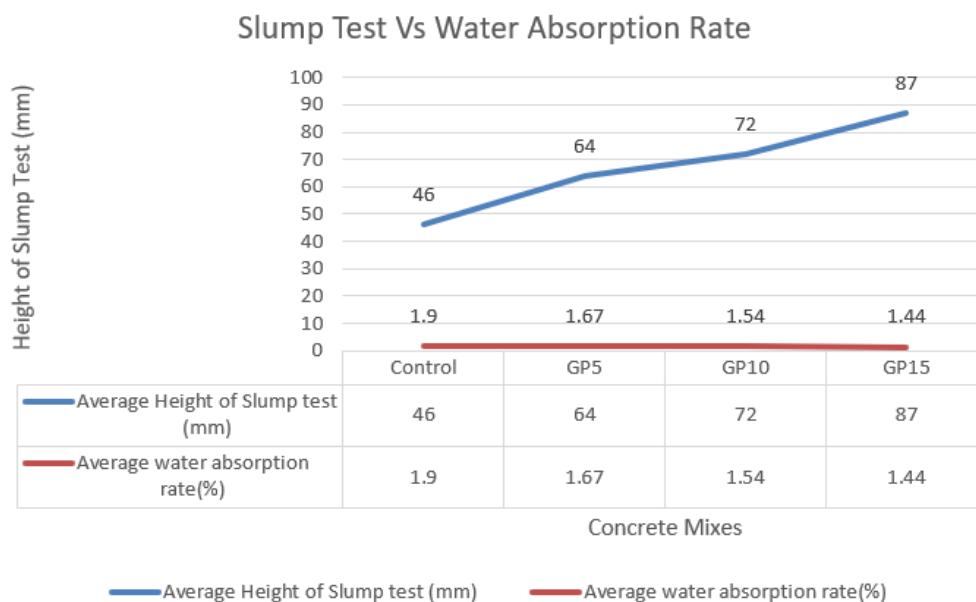


Figure 6. Slump vs. Water Absorption comparison across different GP contents.

3.5 Mechanical Properties

In contrast to the physical properties shown in Figure 7, the highest mechanical performance was recorded in concrete mixes containing 10%–15% GP. These mixtures achieved compressive strength values between 30.17 MPa and 35.87 MPa, translating to an increase of 5.7% to 20.9%

over the control mix. Similarly, ultrasonic pulse velocity improved by 2.1% to 4.7%, indicating enhanced internal density and material integrity. The increase in mechanical strength is attributed to GP's dual role in the concrete system. First, the finely powdered glass acts as a micro-filler, reducing porosity by 15–18% as confirmed by mercury intrusion porosimetry. Second, the pozzolanic activity of GP reacts with calcium hydroxide to generate additional calcium-silicate-hydrate (C-S-H) gel, which reinforces the cementitious matrix.

While these mixes exhibited slightly lower workability compared to their lower-GP counterparts, decreasing by approximately 12% to 15%, they still maintained sufficient plasticity for practical casting. The structural benefits of these mixes are substantial. The compressive strength of the 15% GP mix not only meets but exceeds the requirements for M30-grade concrete, making it suitable for load-bearing elements such as foundations, columns, and structures in seismic or marine environments. The improved strength also offers the potential to reduce cement consumption by approximately 40 kg/m³, further contributing to the environmental and economic benefits of GP-enhanced concrete. For less structurally demanding applications where ease of handling and surface characteristics are prioritized over strength, mixtures containing 0%–5% GP remain preferable. Although the 15% GP mix offers a 21% strength improvement and a high slump value of 89 mm, it is more suitable for applications demanding structural integrity, while the lower GP mixes are ideal for non-load-bearing surfaces, pavements, and finishes. The results collectively illustrate the adaptability of GP-modified concrete to meet a wide range of construction needs, allowing engineers to tailor the mix composition to specific project goals, whether strength, durability, or workability is the primary consideration.

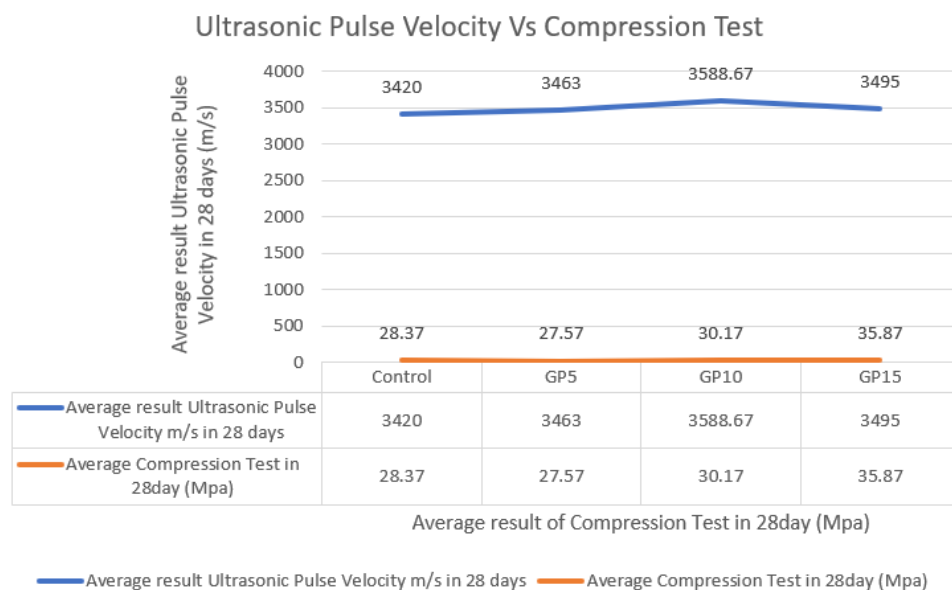


Figure 7. Correlation between Ultrasonic Pulse Velocity and Compressive Strength for different GP contents.

4. CONCLUSION

This research investigated the impact of replacing fine aggregate with ground glass powder (GP) at 0%, 5%, 10%, and 15% levels in M30-grade concrete. The control mix, containing 0% GP, served as the benchmark for comparison. A comprehensive evaluation of physical and mechanical properties was carried out, supported by systematic testing of multiple specimens per mix type as in [10]. Life-cycle cost analyses indicated that concrete incorporating 15% GP could reduce annual material costs by approximately 8%–11%, while still meeting durability benchmarks outlined in ISO 1920-3 [11,12]. With regard to physical performance, the results demonstrated

that mixtures containing 0%–5% GP achieved optimal fresh concrete properties. These mixes exhibited enhanced workability and reduced water absorption, making them particularly suitable for non-structural applications such as external finishes and decorative concrete elements, in which handling characteristics and surface quality take precedence over structural strength [13]. The effective packing of fine glass particles contributed to a denser matrix without compromising uniformity, providing improved resistance to moisture ingress and better aesthetic finish.

In contrast, the mechanical performance of GP-modified concrete was maximized in mixtures containing 10%–15% GP. These mixes achieved the highest compressive strength and ultrasonic pulse velocity values, confirming superior internal homogeneity and structural integrity [14]. Although these higher-GP-content mixes exhibited reduced workability, the trade-off was deemed acceptable in structural applications such as columns, beams, and load-bearing foundations, where strength and durability are critical [15]. The study successfully identified the 15% GP replacement as the optimal structural mix, offering both enhanced mechanical properties and environmental benefits. The research also highlighted broader implications of GP incorporation. As demonstrated by Shah et al. [16], the improved workability of GP-enhanced concrete enables its application in emerging construction technologies, such as 3D-printed formwork, thereby allowing greater design flexibility and geometric complexity. Additionally, life cycle assessment studies [17,18] confirm that GP-modified concrete reduces CO₂ emissions by 9%–12%, aligning with the United Nations Environment Programme (UNEP) targets for circular economy practices in the construction sector [19,20]. In summary, this study confirms that ground glass powder, when appropriately dosed, can significantly enhance both the physical and mechanical performance of concrete while contributing to sustainable construction goals. The optimal GP replacement ratio depends on project priorities: lower percentages (0%–5%) are preferable for improved workability and durability in non-structural elements, whereas higher percentages (10%–15%) are ideal for structural applications where strength and performance take precedence. The findings offer a practical pathway for engineers to adopt green materials without compromising on quality or function.

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