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Mechanical Strength Evaluation of Concrete with Multi-Source Industrial By-Products as Supplementary Cementitious Materials

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Abstract

Concrete production leads to the emission of numerous greenhouse gases into the atmosphere, which are responsible for global warming. Experimental works were conducted to establish the potential utilization of several industrial waste/by-products in concrete production. Currently, the disposal of industrial waste material is a problem for the industry, hence an environmental pollution concern. This study aimed to evaluate the compressive strength of concrete containing various industrial wastes such as GGBS, brick dust, glass, and clinical ash for the benefit of domestic infrastructure purposes. Concrete cubes of 50 mm x 50 mm x 50 mm with different ratios of industrial by-product material ranging from 10% to 40% were cast and water-cured for 7, 28, and 90 days prior to the strength test. The results obtained showed that the partial replacement of cement with multi-source industrial by-products resulted in acceptable strength development. These results suggest technological, economic, and environmental advantages of using industrial waste to achieve sustainable development goals (SDGs).

Keywords: Industrial by-product, Mechanical strength, Concrete, Sustainable material

1. Introduction

Concrete has been recognized as the most essential building material for infrastructure elements. Ordinary Portland Cement (OPC), which is the main element of concrete is made up of four clinker phases known as, alite (Ca3SiO5), belite (Ca_2SiO_4), tricalcium aluminate ($Ca_3Al_2O_6$), and ferrite ($Ca_2(Al_xFe_{2-x})O_5$) with small amount of gypsum ($CaSO_4•2H_2O$) and limestone ($CaCO_3$) (Kunther et al., 2017). Cement provides several advantages, such as high setting time, cost-effectiveness, availability, etc. However, as far as environmental issues are concerned, the production of cement sparks controversy due to its high energy consumption during the manufacturing process, as the combustion of fossil fuels in the kiln generates a substantial amount of CO_2 due to the decomposition of limestone. Cement production involves various polluting substances to the environment, such as carbon dioxide (CO_2), nitrogen oxides (NO_2), Sulphur dioxide (SO_2), and micro dust particles (Nighot & Kumar, 2023). Therefore, to reduce the high energy consumption made by cement production, industrial waste or by-product material was introduced as an option for partial replacement of cement.

On the other hand, the disposal of industrial waste/by-products is an environmentally sensitive issue facing municipalities throughout the world. As the environmental quality standards become more stringent and the volume of industrial waste continues to increase, traditional waste disposal methods are coming under increasing pressure to change. One possible long-term solution is recycling industrial waste and utilizing its benefits. Some of the industrial waste materials possess cementitious and pozzolanic characteristics, which exhibit similar properties or even greater than those of OPC concrete. The use of industrial waste as pozzolanic and supplementary cementitious material (SCM) improves the mechanical and durability properties of concrete due to its ability to react with calcium hydroxide ($CaOH_2$) derived by cement hydration to produce secondary hydrated products, calcium-silicate-hydrate (CSH) and calcium-aluminate-silicate-hydrate (CASH).

Ground granulated blast slag (GGBS) is a by-product material from the steelmaking production sectors that contains high amounts of calcium (CaO), Silica (SiO_2), Aluminum (Al_2O_3), and Magnesium (MgO). The pozzolanic reaction of concrete containing GGBS is different from other pozzolan concretes due to the extra reactions of GGBS. Adu-Amankwah et al. (2023) and Kaur et al. (2012) described that the reaction process of GGBS involves two phases of reaction, known as the initial period, in which the reaction is with alkali hydroxide and the period of early hydration, where the GGBS particles subsequently react with $CaOH_2$. This reaction gives a denser microstructure and is prone to improve the properties of the concrete, especially at later ages. Meanwhile, brick dust (BD) is a by-product from the process of cutting, shaping, or grinding bricks. Bricks are usually made of burned clay minerals in which a certain number of amorphous phases of aluminosilicates were formed during this process. Amorphous silicates are known as non-crystalline structures that enable its dissolution in highly alkaline pore solution forms, which are necessary for the pozzolanic activity reaction (Brînduş-Simuţ et al., 2018).

Clinical ash (CA) was classified as hazardous waste material that should be stabilized and conventionally treated before it can be disposed of in the landfill area. The major compositions of the CA were predominantly made up of SiO_2 and Al_2O_3, in which both components influenced the stable glass structure. CA is also rich in calcite in the form of calcium carbonate ($CaCO_3$) derived from significant sources of the world's quicklime and hydrated, or slaked, lime (Kaur et al., 2019). The effect of calcium in CA led to a reduction in the glass polymerization, making the final product resistant to chemical reactions and physical processes. On the other hand, waste glass is composed of a significant part of waste by-products from both the industry and domestic sources. Olofinnade et al. (2017) presented various options to address the issue of glass waste in the environment, but finely ground glass in powder form is the most effective solution for producing eco-friendly concrete to protect the environment. The use of glass powder promptly affects the cement hydration process through the filler effect and the hetero-nucleation of the CSH compound on the glass powder surface (Dobiszewska et al., 2023). Thus, the present work aimed to better understand how different industrial waste materials with varying contents of replacement can affect the compressive strength of the concrete.

Many existing literature has examined the properties of industrial waste material from GGBS, BD, CA, and glass powder as a partial replacement for cement (Jiang et al., 2019; Matalkah, 2023; Vieira et al., 2023). Therefore, it was deemed necessary to detail some fundamental parameters, such as the main chemical compositions of the waste materials, and the effects of such industrial waste materials on mechanical strength properties. GGBS has a chemical composition and properties that are almost similar to those of cement. Research showed that the inclusion of GGBS as a partial replacement for cement exhibited a reduction in early strength due to its slow pozzolanic reaction and hydraulic properties (Ishak, 2022a). The slow early strength performances of concrete containing GGBS were attributed to the dilution effect caused by a decrease in OPC content (Lim et al., 2019). It was also mentioned by a previous study that the CaO content of GGBS is relatively small compared with cement, indicating that the GGBS concrete will require more time to attain the desired strength (Yoon et al., 2022). The high rate of strength gain of GGBS-OPC concrete was noticed at a later age, particularly from the curing age of 28 days to 91 days. A replacement of 20% of GGBS by weight of cement can keep the 28-day compressive strength of the concrete similar to or even greater than that of the control sample (Siddique & Cachim, 2018).

Previous scholars also claimed that the concrete strength could be enhanced by partially replacing the cement content with BD through crushing and further milling of the brick particles. As a result of its chemical composition as well as its fineness, BD exhibited pozzolanic activity and filler effects that provide adequate performance on mechanical and durability properties (Kinuthia & Nidzam, 2011). Generally, researchers agreed that the inclusion of BD by 10 to 20% as a partial replacement of cement resulted in an improvement in compressive strength (Likes et al., 2022). For example, Wong et al. (2018) reported that the inclusion of 20% replacement of BD in concrete could increase the compressive strength up to 7% at 28 days of curing. Bogas et al. (2022) proved that the 28-day compressive strength was increased up to 15% when cement was replaced by 40% of BD. The strength gain was due to the increment in SiO_2 content, which provided a pore refinement effect through a secondary hydration process that made up a denser formation of microstructure in the concrete matrix.

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Previous studies have proved that mortars with strength levels near 10 MPa at 28 days can also be produced and achieve a minimum requirement for specific applications such as masonry work and filling mixtures. For example, Khanzada et al. (2020) investigated the effect of CA on the strength properties of mortars with a cement replacement of up to 10%. The findings show that the incorporation of cement with 9% CA provided the highest strength of 28 days with 13.12 MPa as compared with the other ratios. The use of very low contents of CA could reduce the significant defects and voids due to the reactions of the ash in the cementitious system. Matalkah (2023) mentioned that the CA could also be used as a replacement for fine aggregate in mortars, in which the 90-day strength could be achieved up to 34 MPa when 40% ash was used. The authors reached a consensus that the ideal amount of CA inclusion in the concrete mixture should be no more than 50% of replacement. This situation is due to the matrix displaying weak pozzolanic properties beyond that level.

Fine glass powder has been used as a supplementary cementitious material (SCM) in concrete or mortar, as it contains more than 70% silica. It performs a pozzolanic reaction that leads to the formation of a high amount of CSH production in cementitious mixtures when the glass is pulverized up to microparticle sizes (Abellan-Garcia et al., 2023). The effect of glass powder on the properties of cement composites mainly depends on the fineness of the glass, which prominently occurs at a later age (Khan et al., 2020; Jiang et al., 2019). Research demonstrated that substituting up to 10-30% of cement with glass powder led to an improvement in the strength properties of mortar and concrete (Kalakada et al., 2022; Ortega et al., 2018). The enhancement of the compressive strength properties is associated mainly with the filler effect of glass powder, which leads to the formation of a denser and less permeable cement matrix. The earlier studies from Shi and Zheng (2007) also agreed that cement could be replaced by up to 50% glass powder or more without any adverse consequences.

Despite extensive investigations into the use of individual industrial by-products such as GGBS, BD, CA, and GP as supplementary cementitious materials, most prior studies have evaluated these wastes in isolation, under varying experimental conditions, and often with a primary focus on early-age strength. Comparative analyses that assess these materials within a unified testing framework, particularly in terms of their mechanical performance, microstructural evolution, and durability, are notably limited. Furthermore, the synergistic potential of combining multiple industrial waste materials in concrete mixtures remains unexplored, mainly leaving uncertainties regarding optimal blend ratios and their influence on both early-age and long-term strength development. Variations in chemical composition, fineness, and pozzolanic reactivity across different waste sources further complicate the establishment of generalizable mix design guidelines. Addressing these gaps, the present study offers a systematic evaluation of GGBS, BD, CA, and GP for both individually and in selected combinations, under standardized curing and testing conditions, thereby providing new insights into their comparative performance and potential for sustainable, high-strength concrete production.

2. Research Method

In this study, four blended binder mixtures with different types of industrial by-products were prepared. Ordinary Portland cement (OPC) was used, complying with MS EN 197-1:2013 CEM 1 52.5N standards (Malaysian Standard, 2000), while all industrial by-product materials were sourced from various origins. A total of 120 samples with five types of concrete mixes were made, including control concrete. The binder phases of the concrete comprise a blend of OPC on a mass-for-mass basis with different binary replacements of industrial by-product materials, the ratio varies from 10% to 40%. A control mixture containing 100% OPC was prepared for comparison in each series. The target total binder content was maintained at 6.95 kg/m^3, equivalent to 2.34 kg of sand, 3.95 kg of coarse aggregate, and the respective binder components as shown in Table 1. The natural river sand with a fineness modulus of 2.6 and a size of 2.36mm served as fine aggregate, while crushed granite with a nominal maximum size of 10mm was used as a coarse aggregate. Potable tap water was used for mixing and remained at the exact value of 0.57 for all concrete mixtures. The cube specimens measuring 50 x 50 x 50 mm were prepared in accordance with ASTM C109/C109M-20b. After casting, the specimens were left at room temperature for 24 hours, then demoulded and underwent the standard curing method until the designated testing ages of 7, 28 and 90 days. The compressive strength was carried out according to BS 12390-4: 2000 (BSI, 2000).

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Table 1: Mix designation of OPC concrete containing different proportions of industrial by-product materials

Sample	Mixtures	Percentage (%)					kg/m^3		Water
		PC	GGBS	BD	CA	Glass	Sand	Course Agg	
C1	PC + GGBS	100	0				2.43	3.95	0.57
B1		90	10						
B2		80	20						
B3		70	30						
B4		60	40						
C1	PC + Brick Dust	100		0					
C2		90		10					
C3		80		20					
C4		70		30					
C5		60		40					
C1	PC + Clinical Ash	100			0				
A1		90			10				
A2		80			20				
A3		70			30				
A4		60			40				
C1	PC + Glass Powder	100				0			
G1		90				10			
G2		80				20			
G3		70				30			
G4		60				40			

3. Results and Discussion

The compressive strength of the OPC concrete (control specimens) and the concrete containing BD as partial replacement of cement at various ratios and curing ages of 7, 28, and 90 days is presented in Figure 1. The overall data shows that all concrete mixtures exhibited a significant increase in compressive strength development from 7 to 90 days of curing.

At 7 days of curing, all concrete specimens with a 10% replacement of industrial by-product materials achieved compressive strengths exceeding 10 MPa, ranging from 12.04 to 20.09 MPa, compared with 24 MPa for the control mortar. Among the mixtures, the OPC–BD blend recorded the highest early-age strength. This improvement is attributed to the high SiO_2 content of BD. The additional silica enhances the stability of the final glassy phase in the cementitious matrix (Wong et al., 2018). However, increasing BD replacement beyond 10% resulted in a strength reduction from 7 days onwards, primarily due to the cement dilution effect. Although recycled BD and recycled concrete powder have been extensively studied, uncertainties remain regarding their pozzolanic and hydraulic reactivity at higher replacement levels. Nevertheless, the present findings are consistent with those reported by Likes et al. (2022), who observed that BD contents above 10% contributed mainly to a filler effect, arising from its finer particle size, which provided additional nucleation sites for the growth of secondary hydration products.

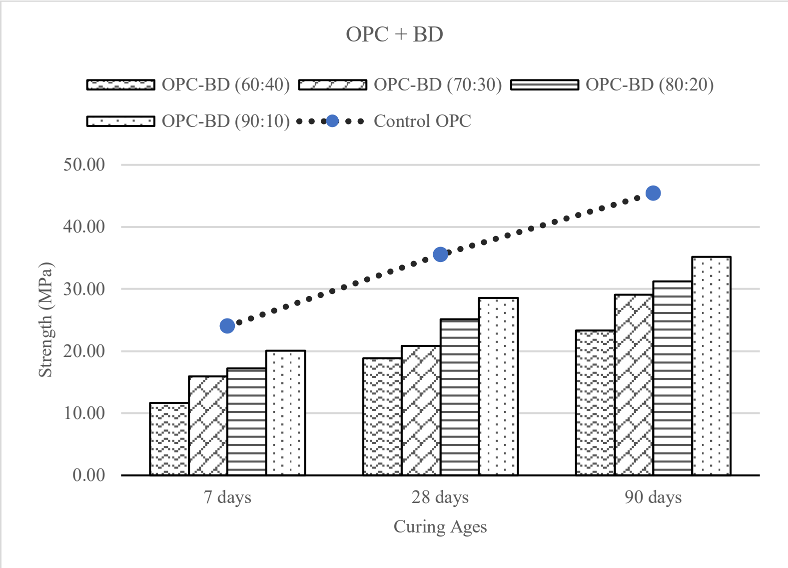

Figure 1 Compressive strength of concrete with partial replacement of BD

Figure 2 presents the compressive strength results of OPC concrete and concrete incorporating GGBS as a partial cement replacement at varying ratios, measured at curing ages of 7, 28, and 90 days. Overall, all mixtures demonstrated a marked improvement in compressive strength with increasing curing duration, particularly at later ages.

The early-age strength of OPC–GGBS concretes showed fluctuating values when the GGBS content increased from 30% to 40%. The optimal performance was observed at 10% replacement, while higher levels increased the risk of cracking and reduced strength development. Slag concretes generally gained strength more slowly than OPC mixtures because GGBS reacts more gradually with water (Ishak, 2022b). Consequently, extended curing is essential to enhance the early-age strength of slag-based mixtures (Adu-Amankwah et al., 2023). At 10% replacement, the siliceous content of GGBS is sufficient to react with $Ca(OH)_2$ to form CSH or CASH gels, with the pozzolanic reaction and filler effect progressively refining voids in the cement matrix (Rafieizonooz et al., 2016). Ban and Kang (2019) reported that GGBS particles form a thin silicic gel and alkali earth hydro-silicate film upon reacting with water, delaying hydrolysis and enhancing strength only at later ages. As curing progressed, all mixtures exhibited notable strength gains, with the highest values consistently achieved at 10% replacement. In contrast, mixes with 30–40% GGBS showed only modest improvements from 28 to 90 days due to the cement dilution effect.

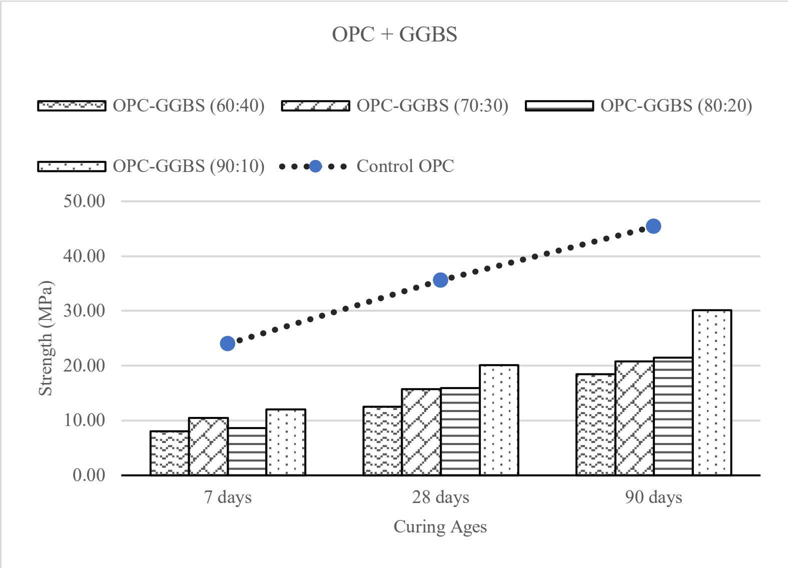

Figure 2 Compressive strength of concrete with partial replacement of GGBS

Figure 3 illustrates the compressive strength development of OPC concrete and mixes incorporating CA as a partial cement replacement at varying proportions, evaluated at curing ages of 7, 28, and 90 days. The results indicate a consistent strength gain across all mixtures with increasing curing duration, with the most notable improvement occurring between 7 and 90 days. This trend reflects the extended pozzolanic activity of CA, which contributes to gradual strength enhancement at later ages compared to OPC concrete.

At 7 days of curing age, the OPC–CA (10%) mix achieved a compressive strength of 19.87 MPa, while mixes with 20%, 30%, and 40% replacement recorded 16.28, 11.77, and 9.57 MPa, respectively. At 28 days of curing age, strength performances for the 20%, 30%, and 40% mixes were lower by 12.80%, 28.44%, and 46.64%, respectively, compared with the 10% mix. By 90 days of curing, these reductions in strength were 8.47%, 41.86%, and 45.04%, respectively. These results indicate that a 10% CA replacement by weight of cement yielded the highest compressive strength across all curing ages. The strength enhancement at this level is attributed to the calcium and silica content of the ash, with the three dominant oxides comprising nearly 75% of its total mass, sufficient to melt the ash and form a glassy phase. Certain compounds, such as $CaCO_3$ and ZnO, act as modifiers that may reduce the strength performances (Sobiecka et al., 2012). The higher later-age strength is associated with the progressive pozzolanic reaction, which increases CSH formation at the expense of CH. Factors influencing this improvement include ash content, reactivity, particle fineness, water-to-binder ratio, and curing conditions (Matalkah, 2023).

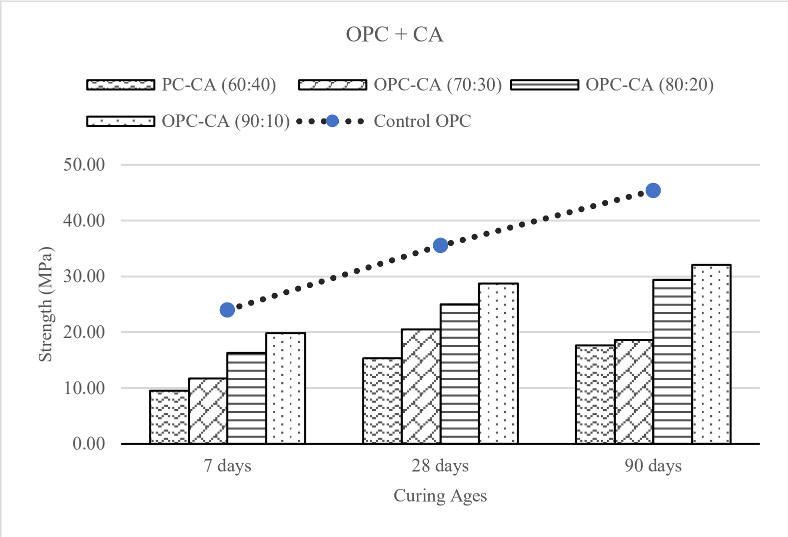

Figure 3 Compressive strength of concrete with partial replacement of CA

Figure 4 presents the strength development results of concretes incorporating waste glass. The results indicated that specimens with 20% glass powder replacement achieved the highest compressive strength among all mixes at 7 days. This improvement is attributed to the combined effects of continued OPC hydration and pozzolanic reactions between the glass powder and CH from the cement matrix. The high silica and calcium contents of the glass powder support its potential as a pozzolanic or cementitious material, consistent with Kalakada et al. (2022) which noted that 10–30% replacement levels yield reasonable strengths. However, at 28 and 90 days, the optimum performance shifted to 10% replacement, with strength decreasing significantly at higher replacement levels. This reduction is linked to morphological changes, micro-crack formation, and weakening of the interfacial transition zone (Olofinnade et al., 2017). Increased replacement levels also intensified cracking due to CSH gel dehydration, driven by a higher alkali–silica reaction between the highly alkaline cement paste and the non-crystalline silica in the glass powder, which may also act as a filler.

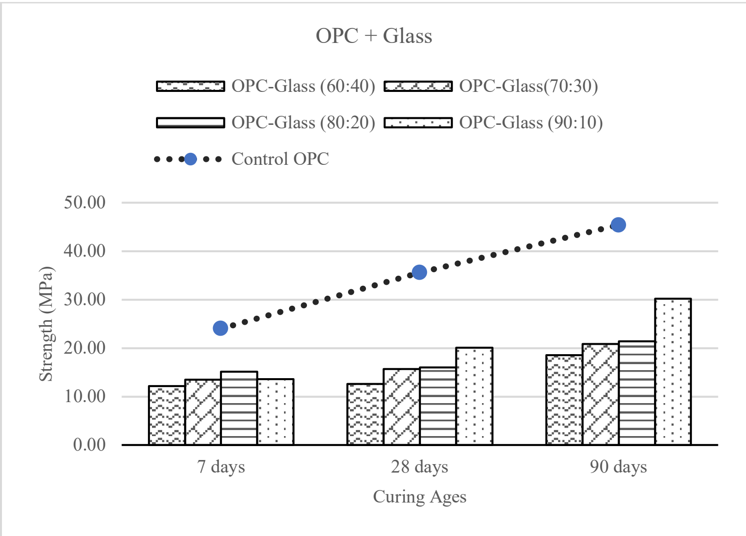

Figure 4 Compressive strength of concrete with partial replacement of Glass Powder

4. Conclusion

The experimental findings indicate that while OPC-industrial by–product material concretes demonstrated enhanced strength development at later ages, the improvement was relatively modest when compared to the control mix. This trend is primarily attributed to the lower heat of hydration exhibited by pozzolanic materials and their comparatively slower reaction with calcium hydroxide (CH) than that of control OPC. Notably, a 10% replacement level of all industrial by-product material, including GGBS, brick dust, glass, and clinical ash, achieved the highest compressive strength, corroborating earlier studies which reported that increasing pozzolanic replacement levels generally diminishes material reactivity. Beyond the replacement proportion, parameters such as the water-to-cement (w/c) ratio, curing duration, and temperature were also found to exert a substantial influence on compressive strength. The progression of both pozzolanic reactions and secondary hydration processes was closely governed by the w/c ratio in conjunction with the intrinsic reactivity of the binder.

The incorporation of industrial waste materials into concrete offers dual benefits. First, it enables the direct recovery of waste products from inert or solid waste management facilities, diverting them from landfills and reducing environmental burdens. Second, by partially replacing cement, it decreases cement consumption and consequently lowers the carbon footprint associated with concrete production. Converting these waste materials into finely powdered form enhances their suitability for use in eco-friendly concrete, owing to their pozzolanic properties and physical characteristics, which closely resemble those of cement and fine aggregates. This approach not only supports sustainable waste management but also provides a technically viable alternative for civil engineers seeking to develop environmentally responsible construction materials while preserving ecosystem integrity.

The use of industrial waste as a source material for concrete showed signs of potential as suggested in recent research, and this merits further in-depth investigations, considering the limited information available. Besides, due to the inherent weakness of industrial wastes, the use of it as a partial replacement of cement should be confined towards low replacement levels for non-structural element purposes, whereby the environmental consideration is given more attention in which the strength and durability of the concrete are not primary requirements. Aligned with the United Nations Sustainable Development Goals (SDGs), notably SDG 9, SDG 12 and SDG 13, this approach promotes industrial symbiosis by transforming waste into value-added resources for the construction sector. This strategy also supports innovation in eco-friendly construction materials while contributing to the broader transition towards a circular and low-carbon economy.

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Authors Contributions
Nuril Izzeaty Ishak processes the data, analyses the results, and writes the manuscript. Norsalisma Ismail designed, reviewed, and wrote the manuscript. Mohamad Nidzam Rahmat reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The authors agree that this research was conducted without any self-beneficial, commercial, or financial conflicts and declare the absence of conflicting interests with the funders.

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