Experimental Methodology for Developing Hybrid Geopolymer Mortar Incorporating Ceramic Waste Powder

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ABSTRACT

Published July Month 2026 The increasing environmental impact associated with Ordinary Portland Cement (OPC) production has accelerated the development of sustainable cement-free construction materials. Among the emerging alternatives, geopolymer mortar has attracted considerable attention due to its lower carbon footprint and excellent engineering performance. This study presents a comprehensive experimental methodology for the development of a fully cement-free hybrid geopolymer mortar (HGM) incorporating ceramic waste powder (CWP) and silica fume (SF) as aluminosilicate precursors activated by sodium silicate. Four binder compositions comprising 100% CWP (Control 1), 90% CWP + 10% SF (C2), 80% CWP + 20% SF (C3), and 70% CWP + 30% SF (C4) were formulated to evaluate the influence of silica fume incorporation on the engineering performance of the geopolymer system. Specimens were cured under three curing regimes consisting of ambient curing (25–30℃), oven curing at 70℃, and oven curing at 100℃ for 24 hours before storage under laboratory conditions. Mechanical performance was evaluated through compressive strength, splitting tensile strength, flexural strength, and ultrasonic pulse velocity (UPV), whereas durability performance was assessed using water absorption, porosity, intrinsic air permeability, capillary absorption, carbonation depth, and drying shrinkage. Microstructural development was investigated using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD). The proposed methodology provides a systematic and reproducible experimental framework for evaluating hybrid geopolymer mortars incorporating ceramic waste and demonstrates an effective approach for transforming industrial ceramic waste into sustainable construction materials suitable for tropical environments.

Keywords: Geopolymer mortar Sustainable construction Ceramic waste powder Hybrid Geopolymer Mortar Silica fume Alkali activated materials

INTRODUCTION

The construction industry is recognised as one of the largest contributors to global greenhouse gas (GHG) emissions owing to the extensive use of Ordinary Portland Cement (OPC). Cement manufacturing alone contributes approximately 7–8% of global carbon dioxide (CO_2) emissions, primarily because of limestone calcination and the high energy demand required during clinker production. Consequently, the development of environmentally sustainable cementitious materials has become an important research priority for achieving global carbon reduction targets. In Malaysia, rapid infrastructure development and urbanization have further increased cement consumption while simultaneously generating large quantities of construction and demolition waste, creating additional environmental and waste management challenges.

Geopolymer technology has emerged as one of the most promising alternatives to conventional OPC-based binders. Unlike cement hydration, geopolymerization involves the alkaline activation of aluminosilicate precursor materials to produce a three-dimensional sodium aluminosilicate hydrate (N–A–S–H) gel network, resulting in materials with excellent mechanical strength, low permeability, and superior durability. In addition to reducing carbon emissions, geopolymer materials enable the beneficial utilization of industrial and agricultural waste, thereby supporting circular economy principles and sustainable construction practices. Although considerable research has focused on fly ash, ground granulated blast furnace slag (GGBS), and metakaolin as geopolymer precursors, the limited availability and increasing cost of these materials have encouraged researchers to investigate alternative aluminosilicate sources that are locally available and environmentally sustainable.

Ceramic waste powder (CWP) represents a promising alternative precursor because of its high silica (SiO_2) and alumina (Al_2O_3) contents, chemical stability, and widespread availability. In Malaysia, substantial quantities of ceramic waste are generated annually from ceramic manufacturing industries, construction activities, and educational institutions. At Universiti Teknologi MARA (UiTM), defective ceramic biscuit specimens produced during practical laboratory sessions are routinely discarded despite containing significant quantities of reactive aluminosilicate compounds. Rather than disposing of these materials in landfills, recycling ceramic waste as a geopolymer precursor provides an environmentally responsible strategy that reduces waste generation while simultaneously producing value-added construction materials. Nevertheless, ceramic waste generally exhibits lower reactivity than conventional geopolymer precursors owing to its partially crystalline structure, which restricts early geopolymerization and strength development.

To overcome this limitation, silica fume (SF) was incorporated as a secondary precursor. Silica fume is an ultrafine industrial by-product containing a high proportion of amorphous silica that enhances geopolymerization by accelerating aluminosilicate dissolution, increasing gel formation, refining pore structure, and improving matrix densification. Previous studies have consistently reported that silica fume significantly improves compressive strength, tensile strength, permeability resistance, and microstructural development in geopolymer systems. Therefore, combining CWP with SF provides a hybrid geopolymer system that simultaneously promotes waste utilisation and enhances engineering performance through improved precursor reactivity.

The curing regime is another important factor influencing geopolymerization. Elevated-temperature curing accelerates precursor dissolution and polymerization, whereas ambient curing more closely represents practical construction conditions, particularly in tropical climates such as Malaysia. Despite increasing interest in ceramic waste-based geopolymers, limited studies have systematically evaluated the influence of different curing regimes on the engineering performance, durability, and microstructural evolution of hybrid geopolymer mortars containing ceramic waste powder and silica fume. Furthermore, many published studies primarily report mechanical properties without establishing a comprehensive relationship between mechanical performance, durability behaviour, and microstructural development.

Accordingly, this study proposes a comprehensive and reproducible experimental methodology for developing hybrid geopolymer mortar incorporating ceramic waste powder and silica fume under three curing regimes: ambient curing (25–30°C), oven curing at 70°C, and oven curing at 100°C. Mechanical properties were evaluated using compressive strength, splitting tensile strength, flexural strength, and ultrasonic pulse velocity (UPV), while durability performance was assessed through water absorption, porosity, intrinsic air permeability, capillary absorption, carbonation depth, and drying shrinkage. The methodology was further validated through microstructural characterisation using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD). The proposed framework provides a systematic experimental protocol that can be readily adopted for future investigations into sustainable geopolymer materials and supports the development of environmentally responsible construction technologies based on recycled ceramic waste.

MATERIALS AND METHODS

Raw Materials

The hybrid geopolymer mortar (HGM) developed in this study was formulated using ceramic waste powder (CWP) as the primary aluminosilicate precursor and silica fume (SF) as a supplementary precursor to enhance geopolymerization. Fine river sand complying with the requirements for mortar production was used as the inert fine aggregate, while commercial sodium silicate (Na_2SiO_3) solution served as the alkaline activator. The selection of these materials was based on their chemical composition, local availability, environmental sustainability, and suitability for alkali-activated binder systems.

Unlike conventional geopolymer binders that primarily utilize fly ash or ground granulated blast furnace slag (GGBS), the present study employed recycled ceramic waste generated from practical activities in the Ceramic Laboratory of Universiti Teknologi MARA (UiTM), Perak Branch. The utilization of ceramic waste not only reduces landfill disposal but also promotes circular economy principles by converting an institutional waste stream into a value-added construction material. Although ceramic waste contains significant amounts of silica and alumina, its relatively low amorphous content results in slower dissolution during alkali activation. Therefore, silica fume was incorporated to improve precursor reactivity and promote the formation of a denser geopolymer matrix.

Ceramic Waste Powder (CWP)

Ceramic waste powder was obtained from discarded ceramic biscuit specimens generated during teaching and practical sessions at the Ceramic Laboratory, Faculty of Creative Arts, Universiti Teknologi MARA (UiTM), Perak Branch. Only unglazed ceramic biscuits were selected because they are chemically stable and contain high proportions of silica and alumina without the heavy metals commonly associated with ceramic glaze waste. The collected ceramic waste was manually cleaned to remove dust and loose contaminants before being mechanically crushed into smaller fragments. Subsequently, the crushed materials were ground using a laboratory ball mill until a fine powder was obtained. The resulting powder was sieved through standard sieves to obtain a particle size between **150 µm and 300 µm**, which was selected to provide an appropriate balance between surface area, workability, and geopolymer reactivity.

X-ray fluorescence (XRF) analysis confirmed that CWP contained predominantly silica (SiO_2) and alumina (Al_2O_3), making it suitable as the principal aluminosilicate precursor. The relatively high silica content enables the formation of sodium aluminosilicate hydrate (N–A–S–H) gel following alkali activation, while alumina contributes to the development of a stable three-dimensional geopolymer framework.

Silica Fume (SF)

Silica fume was incorporated as a highly reactive supplementary precursor to compensate for the relatively low reactivity of ceramic waste powder. The material consisted of ultrafine amorphous silica produced as a by-product of the silicon alloy industry. Owing to its extremely fine particle size and high specific surface area, silica fume enhances geopolymerization by increasing the availability of reactive silica, improving particle packing density, refining the pore structure, and promoting the formation of a denser geopolymer gel network.

The incorporation of silica fume was expected to improve both mechanical and durability performance by reducing pore connectivity and increasing matrix compactness. Previous studies have demonstrated that silica fume enhances compressive strength, tensile strength, permeability resistance, and microstructural development in alkali-activated materials, particularly when combined with low-reactivity precursors.

Fine Aggregate

Natural river sand was used as the fine aggregate throughout this study. Prior to mixing, the sand was oven dried to achieve a constant moisture condition and subsequently sieved to remove oversized particles. Particle size distribution was determined by sieve analysis in accordance with BS 882 requirements to ensure suitable grading for mortar production. The use of well-graded fine aggregate contributes to improved workability, reduced segregation, and enhanced dimensional stability of hardened geopolymer mortar.

Alkaline Activator

Commercial sodium silicate (Na_2SiO_3) solution was employed as the sole alkaline activator throughout this investigation. Unlike many previous geopolymer studies that utilise a combination of sodium hydroxide and sodium silicate, the present study adopted only sodium silicate to simplify the mixing procedure and improve laboratory safety. The sodium silicate solution possessed a silica modulus (SiO_2/Na_2O) of approximately 3.2, a solid content of 40–45%**,** a density of 1.38–1.42 g/cm³**,** and a pH of approximately 11–12, as specified by the manufacturer. The activator supplied soluble silica necessary for dissolving aluminosilicate species from ceramic waste powder and silica fume, thereby initiating geopolymerisation and promoting the formation of sodium aluminosilicate hydrate (N–A–S–H) gel. The physical properties of the sodium silicate solution are presented together with the other raw materials in Table 1.0.

Table 1.0 Properties of raw materials used in Hybrid Geopolymer Mortar

Material	Function	Main Characteristics
Ceramic Waste Powder	Primary alumnosilicate	High SiO_2 and Al_2O_3 content; particle size 150-300μm
Silica Fume	Supplementary precursor	Ultrafine amorphous silica with high reactivity
River Sand	Fine aggregate	Well-graded natural silica sand complying with BS 882
Sodium Silicate	Alkaline activator	Commercial Na_2SiO_3

Mix Design

Four hybrid geopolymer mortar mixtures were formulated to evaluate the influence of silica fume replacement on the engineering performance of ceramic waste-based geopolymer mortar. Ceramic waste powder served as the primary precursor, while silica fume replaced ceramic waste powder at incremental replacement levels of 10%, 20%, and 30%. These replacement levels were selected to systematically investigate the influence of increasing reactive silica content while maintaining a constant total binder content and activator dosage. This experimental design enabled the individual effect of silica fume on geopolymerization, strength development, durability, and microstructural evolution to be evaluated under identical curing conditions.

Table 1.1 Mix design series

Mix Series	Ceramic Waste Powder (%)	Silica Fume (%)
C1	100	0
C2	90	10
C3	80	20
C4	70	30

A constant water-to-binder ratio and sodium silicate dosage were maintained throughout the experimental programme to eliminate variability associated with activator concentration. Consequently, any observed differences in engineering performance could be attributed primarily to the replacement level of silica fume and the applied curing regime rather than variations in mixture proportions.

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Mechanical testing was conducted in accordance with the relevant British Standards and ASTM specifications listed in Table 1.2. Compressive, splitting tensile and flexural strengths were determined using a calibrated universal compression testing machine under displacement-controlled loading. Ultrasonic Pulse Velocity (UPV) measurements were performed before destructive testing to evaluate internal homogeneity and defect distribution. Water absorption, porosity, carbonation depth and capillary absorption tests were conducted according to the corresponding ASTM and BS standards after the designated curing periods. SEM, EDS and XRD analyses were subsequently carried out to investigate the morphology, elemental composition and crystalline phases responsible for the observed engineering performance.

Table 1.2 Testing Standard

Types of Testing	Standard	Specimen
Compressive Strength	BS EN 12390-3	100 x 100 x 100 mm cube
Split Tensile	BS EN 12390-6	100 x 200 mm cylinder
Flexural	BS EN 12390-5	100 x 100 x 500 mm prism
UPV	BS EN 12504-4	Cube & prism
Water Absorption	ASTM C642	Cube
Porosity	ASTM C642	Cube
Carbonation	BS EN 14630	Cube
SEM	ASTM C1723	Fragments
XRD	ASTM C1365	Powder

Table 1.3 Experimental Variables

Variable	Controlled Parameter
Ceramic Waste Powder	70-100%
Silica Fume	0-30%
Sodium Silicate	40% of binder weight
Water/Binder Ratio	0.45
Sand/Binder Ratio	2.75
Curing Temperature	Ambient (25-30°C), 70°C, 100°C
Curing Duration	24h oven dry + ambient curing
Testing Ages	7, 14, 28, 56, 90 days
Number of Replicates	3

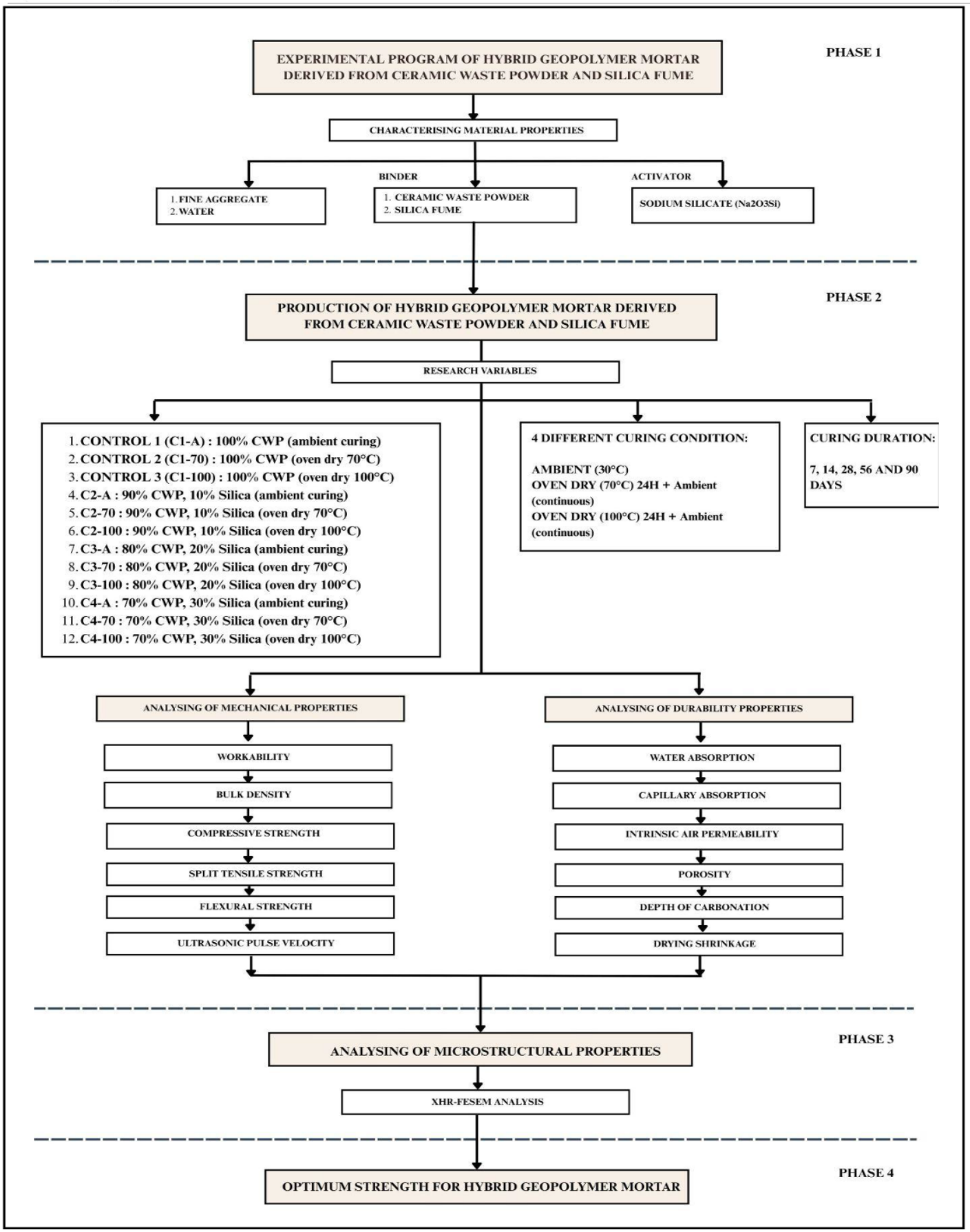

Figure 1.0 Experimental Program Flow for CWP Based Geopolymer Assessment

Constant Mixing Parameters

To ensure that the influence of silica fume replacement could be evaluated independently, all mixtures were prepared using identical mixing parameters throughout the experimental programme. The water-to-binder ratio, sand-to-binder ratio and sodium silicate dosage were maintained constant for all mixtures to eliminate variability associated with changes in activator concentration. Consequently, any variation in engineering performance could be attributed primarily to the replacement level of silica fume and the applied curing regime.

Specimen Preparation

The preparation of hybrid geopolymer mortar was conducted using a systematic mixing procedure to ensure homogeneity. Initially, ceramic waste powder and silica fume were dry mixed to achieve uniform distribution. Fine aggregates were then added and mixed thoroughly before the gradual incorporation of sodium silicate solution. Mechanical mixing was continued until a consistent and workable mortar was obtained.

The fresh mortar was immediately cast into standard moulds corresponding to different testing requirements. Cube specimens with dimensions of 100 × 100 × 100 mm were prepared for compressive strength testing, cylindrical specimens of 100 × 200 mm were used for splitting tensile strength evaluation, and prism specimens measuring 100 × 100 × 500 mm were prepared for flexural strength and ultrasonic pulse velocity (UPV) testing. The specimens were left undisturbed for initial setting prior to curing. Three identical specimens were prepared for each mix series, curing condition, and testing age. The reported values represent the average of three specimens to minimise experimental variability and improve data reliability.

Curing Regimes

Curing is a critical factor influencing the geopolymerization process and subsequent material performance. In this study, three curing regimes were adopted to evaluate their effects on hybrid geopolymer mortar. Ambient curing was conducted at temperatures ranging from 25 to 30°C to simulate real construction conditions in tropical environments. In addition, oven curing at 70°C and 100°C for 24 hours was implemented to accelerate the geopolymerization process and assess the influence of elevated temperatures on strength development.

Following the initial curing period, all specimens were stored at room temperature until the designated testing ages. The use of multiple curing regimes allowed for a comprehensive evaluation of both practical and accelerated curing conditions.

RESULTS AND DISCUSSIONS

The mechanical performance of hybrid geopolymer mortar (HGM) was evaluated through compressive strength, splitting tensile strength, flexural strength, and ultrasonic pulse velocity (UPV) at curing ages of 7, 14, 28, 56, and 90 days. The results demonstrated a clear influence of both precursor composition and curing regime on strength development. In general, all mixtures exhibited progressive strength gain with increasing curing age, indicating the continuous geopolymerization process and gradual formation of a stable aluminosilicate network.

Among the mix compositions, specimens containing silica fume (C2, C3, and C4) consistently outperformed the control mixture (C1). This improvement can be attributed to the presence of highly reactive amorphous silica in silica fume, which enhances dissolution and polycondensation reactions during geopolymerization. The incorporation of silica fume significantly improved matrix densification, resulting in higher compressive strength values. Mixes C3 and C4, containing 20% and 30% silica fume respectively, exhibited the highest strength due to optimal precursor synergy and enhanced gel formation.

The compressive strength development of hybrid geopolymer mortar is presented as a function of curing age and mix composition. All mixtures exhibited a progressive increase in strength from 7 to 90 days, indicating continuous geopolymerization. At later curing ages (56 and 90 days), strength gains became more gradual, with

C3 and C4 maintaining superior performance. The increase in compressive strength between 28 and 90 days was observed to be approximately 10–20%, reflecting continued geopolymerization and matrix densification.

The splitting tensile and flexural strength results followed a similar trend to compressive strength, confirming the improved bonding and cohesion within the geopolymer matrix. The increase in tensile related properties indicates that the addition of silica fume not only enhances compressive resistance but also improves resistance to crack initiation and propagation. This behavior is closely related to the refinement of the microstructure and reduction of internal defects.

Ultrasonic pulse velocity (UPV) measurements further supported these findings, as higher UPV values were recorded for silica fume-rich mixtures. The increase in UPV indicates improved internal homogeneity and reduced void content, confirming the formation of a denser and more continuous geopolymer matrix. Ultrasonic pulse velocity (UPV) measurements further confirmed improvements in internal structure.

Influence of Curing Regimes

Curing conditions played a critical role in determining the performance of hybrid geopolymer mortar. The results indicated that elevated temperature curing significantly influenced early strength development, while long-term performance depended on the balance between reaction kinetics and structural stability.

Specimens cured at 70°C demonstrated the most stable and consistent performance across all mix compositions. The moderate thermal energy provided by this curing regime enhanced the dissolution of aluminosilicate precursors and accelerated geopolymerization without inducing excessive thermal stress. As a result, specimens exhibited higher strength and improved durability compared to other curing conditions.

In contrast, curing at 100°C resulted in rapid early strength gain due to accelerated reaction kinetics. However, prolonged exposure to high temperatures led to the development of microcracks within the geopolymer matrix. These microcracks can be attributed to thermal shrinkage and differential moisture loss, which negatively affect long-term mechanical performance.

Ambient curing, although more sustainable and representative of real construction conditions, resulted in slower strength development due to limited thermal activation. Nevertheless, the results indicate that acceptable performance can still be achieved under ambient conditions, particularly in mixtures containing higher silica fume content, which compensates for the lower reactivity of ceramic waste powder.

Durability Performance

The durability performance of hybrid geopolymer mortar was evaluated through water absorption, porosity, capillary absorption, intrinsic air permeability, carbonation depth, and drying shrinkage. These properties are critical in assessing the long-term behavior of materials under environmental exposure. Durability results revealed a significant improvement with increasing silica fume content. Water absorption values decreased from approximately 8–10% in C1 to 5–7% in C4, representing a reduction of nearly 30–40%. This reduction indicates improved pore refinement and reduced permeability.

The results showed a significant reduction in water absorption and porosity with increasing silica fume content. This reduction is primarily attributed to the improved packing density and refinement of pore structure within the geopolymer matrix. The addition of silica fume effectively fills microvoids and enhances the formation of gel phases, resulting in a less permeable and more durable material. Porosity values showed a similar trend, decreasing from 18–22% (C1) to 12–15% (C4). The reduction in porosity is directly associated with improved packing density and geopolymer gel formation.

Intrinsic air permeability and capillary absorption results further confirmed the improvement in durability. Mixtures with higher silica fume content exhibited lower permeability, indicating reduced connectivity of pore

networks. This characteristic is essential for improving resistance to aggressive environmental conditions, including moisture ingress and chemical attack. Intrinsic air permeability was reduced significantly in silica fume-rich mixtures, with values decreasing by approximately 40–60% compared to the control mix. Capillary absorption rates also decreased, indicating reduced water transport within the matrix.

Carbonation depth was also found to decrease with increasing silica fume content, suggesting enhanced resistance to CO_2 penetration. This behavior is closely related to the densification of the matrix and reduction in pore size distribution. Similarly, drying shrinkage was minimized in silica fume-rich mixtures due to improved structural stability and reduced moisture loss. Carbonation depth measurements indicated improved resistance to CO_2 penetration, with C4 showing approximately 30–50% lower carbonation depth compared to C1. Drying shrinkage values were also reduced in hybrid mixtures, with reductions of approximately 10–20%, indicating improved dimensional stability.

Overall, the durability results highlight the effectiveness of hybridization in improving the long-term performance of geopolymer mortar.

Microstructural Characteristics

Microstructural analysis was conducted using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD) to understand the internal structure and phase development of hybrid geopolymer mortar.

SEM observations revealed significant differences between the control and modified mixtures. The control mixture (C1) exhibited a relatively porous structure with visible unreacted particles, indicating incomplete geopolymerization. In contrast, mixtures containing silica fume (C3 and C4) showed a dense and compact microstructure with fewer voids and improved particle bonding. The presence of a continuous gel matrix confirmed enhanced geopolymerization. SEM analysis revealed that the control mix (C1) exhibited a relatively porous microstructure with visible unreacted particles. In contrast, C3 and C4 showed a dense and compact matrix with fewer voids and improved particle bonding. The reduction in voids was estimated to be consistent with the observed 30–40% reduction in porosity.

EDX analysis indicated an increased presence of silicon and aluminum elements in silica fume-rich mixtures, supporting the formation of geopolymer gel phases. The improved Si/Al ratio contributes to the development of a stable three-dimensional network, which is essential for strength and durability.

XRD analysis further confirmed the formation of amorphous geopolymer gel phases, primarily sodium aluminosilicate hydrate (N–A–S–H). The reduction in crystalline peaks and the presence of broad humps in diffraction patterns indicate the transformation of raw materials into geopolymer products. This transformation is more pronounced in mixtures with higher silica fume content. XRD patterns showed a broad amorphous hump between 20°–35° (2θ), indicating the formation of N–A–S–H gel. The intensity of crystalline peaks decreased with increasing silica fume content, confirming enhanced geopolymerization.

Relationship between Microstructure and Performance

A strong correlation was observed between microstructural characteristics and mechanical and durability performance. The densification of the geopolymer matrix, as observed in SEM analysis, directly contributed to increased strength and reduced permeability. The formation of N–A–S–H gel phases enhanced the binding properties of the material, resulting in improved load-bearing capacity.

The reduction in porosity and refinement of pore structure played a crucial role in enhancing durability performance. Lower porosity limits the ingress of water and harmful agents, thereby improving resistance to environmental degradation. This relationship highlights the importance of optimizing precursor composition to achieve desired performance outcomes.

CONCLUSION

This study presents a structured and practical approach to developing hybrid geopolymer mortar (HGM) using ceramic waste powder (CWP) and silica fume (SF) as the main binding materials. By combining careful material preparation, well-planned mix design, different curing conditions, and detailed performance testing, a clear and reproducible methodology has been established for producing sustainable geopolymer mortar.

The findings show that adding silica fume plays a key role in improving the overall performance of the material. Mixes containing 20–30% silica fume (C3 and C4) consistently performed better in terms of compressive, tensile, and flexural strength, reaching strengths of over 5 MPa at later curing stages. This improvement is mainly due to better geopolymer reactions, stronger gel formation, and a denser internal structure. The ultrasonic pulse velocity (UPV) results also supported this, showing that these mixes had a more uniform and compact internal matrix.

Curing conditions were also found to have a strong influence on performance. Curing at 70°C provided the best overall results, offering a good balance between strength development and structural stability. While curing at 100°C helped the material gain strength quickly at early ages, it also introduced small internal cracks that slightly reduced long-term performance. On the other hand, ambient curing was slower but still produced acceptable results especially for mixes with higher silica fume content showing that this material can perform well under real construction conditions.

In terms of durability, the inclusion of silica fume significantly improved resistance to environmental effects. Lower water absorption, reduced porosity, and decreased permeability were observed, indicating a more compact and less penetrable material. Carbonation resistance and shrinkage performance also improved, suggesting better long term stability. These improvements are closely linked to the refinement of the pore structure and stronger bonding within the geopolymer matrix, as confirmed by microstructural analysis.

A clear relationship between internal structure and performance was observed. As the matrix became denser and less porous, both strength and durability improved. This highlights the importance of optimizing the mix composition to achieve a well developed geopolymer structure.

Although the present study demonstrates the technical feasibility of hybrid geopolymer mortar incorporating ceramic waste powder and silica fume, further research is recommended to evaluate its environmental and economic sustainability through life-cycle assessment (LCA), embodied carbon analysis and cost-benefit assessment relative to conventional Ordinary Portland Cement (OPC) mortar. Future studies may also employ advanced optimisation techniques, such as Response Surface Methodology (RSM), together with long-term field exposure investigations under aggressive environmental conditions to optimise mix proportions and validate long-term performance.

Overall, the study demonstrates that hybrid geopolymer mortar made from ceramic waste powder and silica fume is not only technically viable but also environmentally beneficial. It offers a practical way to reuse waste materials while reducing dependence on conventional cement. Based on the results, a silica fume content of around 20% appears to provide the best balance between performance and material efficiency. The developed material shows strong potential for use in construction, particularly in areas where ceramic waste is readily available.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Muhammad Naim Mahyuddin: Conceptualization, methodology, formal analysis, investigation and writing-original draft; **Sallehan Ismail**: supervision, writing-review and editing, and validation; **Azamuddin Husin**: supervision, writing-review and editing, and validation; **Nor Nazida Awang**: supervision, writing-review and editing, and validation; **Mohd Najib Abd Rashid**: Conceptualization, formal analysis, and validation; **Farrah Rina Mohd Roshdi**: Conceptualization, formal analysis, and validation.

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