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Recycled Glass Powder and Eggshell Powder as Supplementary Cementitious Materials in Concrete for a Global Shift Towards Sustainable Production

Laksham Sanassee[1, a)], Abdus Cadersa [2]

[1] *Mechanical and Production Engineering Department, University of Mauritius, Port-Louis, Mauritius*
[2] *Civil Engineering Department, University of Mauritius, Port-Louis, Mauritius*

[a)] Corresponding author: l.sanassee@uom.ac.mu

Abstract. Solid waste management presents a significant global challenge, demanding innovative and sustainable solutions. Recycling waste into construction materials is a promising approach for sustainable development. Eggshells and glass wastes can be recycled to recover valuable materials. This study investigates the amalgamation of these two waste materials for partial cement replacement in mortar and concrete and focuses on the impact of varying recycled glass particle (GP) size within concrete mixtures containing 75 µm eggshell powder (ESP). Mortar specimens were prepared with a 1:3:0.5 cement: sand: water ratio, incorporating 10% and 15% (by weight of cement) of treated and untreated ESP, along with recycled GP. Results indicated that a 10% cement replacement ratio yielded optimal compressive strength. Notably, mortar containing 10% recycled GP (75 µm) exhibited superior compressive strength compared to ESP of the same size. Interestingly, calcination treatment of ESP did not significantly impact 28-day compressive strength compared to untreated eggshell mortar. However, calcination appeared to accelerate the hydration process during casting. Based on these findings, subsequent concrete testing employed only 10% untreated ESP and GP as partial cement replacements. The investigation focused on the effect of GP particle size (45 µm and 75 µm) on the mechanical properties of the concrete mixtures. Concrete containing 75 µm GP achieved a higher compressive strength after 28 days compared to ESP of the same size. Further reduction of the GP particle size to 45 µm resulted in a significant increase in compressive strength (almost 50%) exceeding traditional concrete mixtures by 6%. However, this improvement came at the cost of reduced workability in the concrete mix. Similarly, ESP-GP mixtures containing GP of particle size 45 µm displayed increased compressive strength (27.6 MPa) compared to the ESP-GP mixtures containing particle size of 75 µm after 28 days. Additionally, the split tensile strength of the ESP-GP concrete mix also improved with the reduction of GP particle size. These findings suggest that incorporating recycled GP, particularly with a finer particle size (45 µm), presents a promising strategy for enhancing the mechanical properties of concrete containing ESP as a partial cement replacement.

Keywords: Eggshell powder; glass powder; sustainability; waste material recycling; cement replacement

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INTRODUCTION

The construction industry plays a crucial role in shaping a country's economic well-being, leaving a deep impact on its financial landscape. Around the world, concrete is the most commonly used material in construction. It consists of cement, fine and coarse aggregates and water. The mixture hardens over time through a chemical reaction known as hydration between the cement and water. The cement industry is ranked among the highest emitters of greenhouse

gases, with approximately 1 tonne of carbon dioxide (CO_2) per tonne of cement [1]. Moreover, significant energy and natural resources are required in its manufacturing process to meet the global demand of 4 billion tonnes annually [2]. Hence, reducing cement content in concrete production and incorporating recycled materials are pressing issues for the global concrete industry in the 21st century [3]. Moreover, the growing scarcity of natural resources and the mounting problem of industrial waste are driving researchers to explore the use of waste products as supplementary cementitious materials (SCM) in concrete. This approach is crucial for protecting the environment, promoting sustainable use of resource and cuts down on carbon dioxide emissions. Reducing our dependence on natural resources, minimizing energy consumption, implementing sustainable waste disposal methods, and lowering CO_2 emissions are critical global issues that must be addressed to achieve cleaner production and build a more sustainable future.

There is a significant chance to fight climate change and conserve resources by using SCMs or alternative materials for partial replacement of cement in concrete [4]. Studies have demonstrated that SCMs such as ground granulated blast furnace slag and fly ash used in concrete mixes can significantly reduce CO_2 emissions [5] [6]. In fact, compared to using only cement, slag can cut CO_2 by roughly 49.6%, while fly ash achieves a reduction of around 28.9% [7]. To adhere with sustainable development goals, governments are phasing out coal-fired power plants, thus reducing the availability of fly ash and resulting to a supply shortage in some regions for the production of concrete [8]. Thus, many researchers are increasingly exploring waste materials as SCM for sustainable concrete production [[9] [2] [10]].

Chicken eggshell waste disposed in large quantities by fast-food establishments, hotels, households, poultry industry and large-scale liquid egg production, is a form of food waste that poses ecological challenges due to its organic protein matrix, attracting pests like worms and rats [2]. Given the rich content of calcium carbonate ($CaC0_3$) in eggshells (ES), several researchers have explored their potential in various applications such as biodiesel catalyst, fertilizer, absorbent of heavy metals and medical products in an effort to valorize post-consumer wastes and reduce industrial by-products entering the landfills [11]. In concrete production, investigations have been carried out to assess their feasibility as binder replacement [12], filler [13] and fine aggregates [14]. As the global egg production and consumption is expected to increase beyond 1360 billion eggs, with estimates suggesting a 50% increase by 2035 [14], there is a need to investigate eggshells as a substitute for traditional cement and their effect on the properties of concrete when different replacement levels are used in combination with other additives.

Another potential waste with pozzolanic activity is glass. Glass is extremely valuable around the world because of its unique properties such as resistance to chemical, high strength and low permeability [15]. Even though glass is endlessly recyclable, some recycled glass doesn't meet the high standards needed for new products. This means a significant portion ends up in landfills, with estimates suggesting around 200 million tons of glass are landfilled globally each year, reflecting a low overall recycling rate [16]. Due to its abundance and non-biodegradable properties, recycled glass powder (GP) at micro-meter scale can be a good substitute for cement in many applications with high yield and low price [17].

With a growing focus on sustainability in construction globally, recycling waste to create eco-friendly building material is merging as a key solution. This study investigates the use of ESP in combination with GP as partial replacement of cement for producing eco-friendly concrete. So far, these two waste materials have been investigated in isolation and have both showed great potential to significantly contributes to resources preservation and carbon footprint reduction. Thus, the amalgamation of the two waste materials in concrete would provide a sustainable waste management strategy within a global shift towards a sustainable value chain for the production of concrete through the valorization of waste to curb environmental impacts while supporting the implementation of SDG11: Sustainable Cities and Communities & SDG12: Responsible Consumption and Production. Workability, compressive strength, and split tensile strength were evaluated in order to offer a comprehensive and practical guide for GP and ES utilization as a sustainable cement replacement in concrete.

LITERATURE REVIEW

Chicken Eggshell Powder (ESP) as a Partial Cement Replacement

Rich in calcium carbonate ($CaC0_3$) in the form of calcite with a percentage by weight ranging from 94-97%, ESP is similar in composition to mineral limestone which is used as one of the four raw materials for cement production [18]. In addition to limestone, cement also contains dicalcium silicates (C_2S), tricalcium silicate (C_3S), tricalcium aluminate (C_3A) and tetra-calcium aluminoferite (C_4AF) [19].Studies have shown slight variations in eggshell

composition due to factors such as chicken population density, strain, genetics, age and diet [20]. For example, brown eggshells are mostly made of 96–97% $CaC0_3$ with 3–4% organic membrane [21], while white eggshells have around 94% calcium carbonate and 6% organic membrane [22]. Despite minor differences, eggshells consistently boast a high calcium carbonate content, making them a promising alternative for lime production.

Pretreatment are conducted to recover $CaCO_3$ from eggshells, which is used as partial cement replacement. A study by Diningsih and Rohmawati [23] employed a simple calcination method to achieve 100% calcite $CaCO_3$ phase from eggshells. The ES were washed, sun-dried, soaked in sodium hypochlorite solution and calcinated at 250°C for 10 minutes. X-Ray diffraction (XRD) confirmed 100% calcite $CaCO_3$ phase, and FTIR identified Ca-O, C-O, $-CH_2$, and O-H functional groups. The synthesized $CaC0_3$ demonstrated light absorption at specific wavelengths, indicating an energy band gap of 3.91 eV. Yoo et al. [24] created a cost-effective separation unit called dissolved air flotation (DAF) for effectively recovered 96% of the eggshell membrane and 99% of the eggshell calcium carbonate (ECC) particles from eggshell waste in just 2 hours.

According to the literature review, some studies have shown that replacing cement with ESP in concrete results in better mechanical properties. Salama [25] and Chong et al. [2] both confirmed that incorporating eggshell powder (ESP) in mortar and partially substituting cement increased the compressive strength. This is attributed to ESP's filling effect and high calcium content, promoting hydration and enhancing mortar strength. The presence of $CaCO_3$ positively influenced cement paste hydration by delaying ettringite transformation, leading to the formation of denser C-S-H gel and reduced voids. However, beyond the optimum percentage, ESP addition increased water demand, raising the water-cement ratio and decreasing mechanical strength. Auta et al. [13] utilized Portland limestone cement CEM II 42.5R in mortar, with varying proportions of ESP as a cement replacement. Results indicated higher compressive strength at an 8% ESP ratio.

Similarly, Kumar et al. [26] found a replacement ratio of 5% with ESP particles less than 90 microns resulted in a 5% increase in compressive strength at day 7 and an 11.1% increase at day 28. The elevated early strength is attributed to available lime in the ESP matrix, accelerating hydration through carboaluminate synthesis. This favors over monosulfate due to C_3A interaction with $CaCO_3$. Additionally, early production of $Ca(OH)_2$ provides more nucleation sites when combined with $CaCO_3$ from ESP, enhancing early strength. Vaidya and Bastwadkhar [27] used ESP particles below 90μm to evaluate compressive strength after 28 days and the result showed a substantial 7.15% increase in compressive strength with 10% ESP as a cement replacement. Jhatial et al. [12] found that the improvement in compressive strength is better with finer particle size ESP. With 50 μm ESP and a 10% replacement ratio, the compressive strength is increased by 7.47%, 10.52%, and 5.88%, at 3, 7, and 28 days respectively. Meanwhile, Tan et al. [28] obtained a higher compressive strength with 15% ESP replacement ratio eggshell powder with particles smaller than 60 μm.

Glass Powder (GP) as a Partial Cement Replacement

Glass contains high amount of Silica (SiO_2) and can be an ideal pozzolanic material [29]. Currently, researchers are exploring the use of GP as a replacement for aggregate or cement. GP in concrete may cause alkali-silica reaction (ASR) but reducing particle size to below 0.30 mm transforms it into a pozzolanic material [30]. The ASR is a chemical reaction that occurs between the reactive elements of cement aggregates and the alkali, K^+ and Na^+, and hydroxyl (OH^-) ions found in the interstitial concrete pore solution [31]. Integrating sufficient glass as a supplemental cementitious material reduces aggregate reactivity and expansion. Pozzolanic materials, characterized by high silica content, X-ray amorphous nature, and wide surface area, react with free lime in cement, forming hydrated products with binding properties [32]. This enhances microstructure, minimizes micro pores, and improves cementitious material performance. GP with its silica content and amorphous nature, exhibits pozzolanic behavior, creating a denser matrix according to microstructural analysis [33].

Pereira-de-Oliveira et al. [34] examined the pozzolanic activity of GP of various size as partial replacement for ordinary Portland cement in mortar. Despite a reduction in compressive strength with glass powder addition, the 10% replacement ratio yielded optimal results. Strength activity index assessment, following EN 450 standards, indicated that particle sizes of 0–45 μm and 45–75 μm demonstrated potential pozzolanic activity. However, the 75–150 μm range fell short of the 90-day criteria, suggesting insufficient pozzolanic activity. Similarly, Ramasamy and Govindarajan [35] recorded a reduction in compressive strength due to rise in porosity and lower cement content as the GP replacement ratio is increased in the mortar mixture.

Raju and Kumar [36], used 45 μm GP as partial replacement of cement for concrete in the range 5% to 40%. As the replacement ratio is increased, the workability of the concrete is reduced and concrete with 20% GP replacement exhibited higher compressive strength. The high silica content of GP induced a pozzolanic reaction. This also

contributed to a denser concrete microstructure and effective void filling. However, beyond a 20% replacement ratio, a dilution effect occurred as the reduction in cement content negatively impacted hydration products, porosity, permeability, and compressive strength at both early and later ages. On the other hand, Harish et al. [33] obtained a decreased in compressive strength and split tensile strength for GP particle sizes at 300 µm. However, further reducing the GP to less than 150 µm, increased the compressive strength. Similarly, Zeybek et al. [37] also observed a reduction in compressive strength and split tensile strength for all cement partial replacement ratios, with optimal strength at 10% GP replacement ratio.

However, there is a lack of research on the use of ESP in combination with GP as partial cement replacement to achieve economic and environmental advantages with the production of new sustainable concrete by reducing the use of non-renewable raw materials. Multiple studies investigating the use of ESP in isolation have identified a 10% - 15% replacement ratio for optimal performance [[38] [39] [40] [41]]. Furthermore, it is reported that 10–20 wt% cement replacement by GP has led to satisfactory results [37] [42] [43]. Based on these conclusions, concrete mixtures were investigated with GP and ESP as partial cement replacement of ratio 10% and 15% by volume, both individually and when used together in the design mix. The effect of GP particle size on the mechanical properties of concrete containing ESP was also examined by conducting a series of compressive strength and splitting tensile strength tests.

EXPERIMENTAL

Materials

Chicken eggshells wastes were collected from a local restaurant and hotels, washed, and allowed to dry in the atmosphere. They were then crushed into fine powder using a planetary ball milling machine for 1 hour and sieved in a rotary shaker to obtain untreated eggshell powder of uniform particle size 75 µm. Calcium Carbonate ($CaCO_3$) was extracted from chicken eggshells waste using calcination method proposed by Diningsih & Rohmawati [23]. The shells were cleaned with distilled water and dried in sunlight. They were then soaked in 6% sodium hypochlorite (NaOCl) solution for 6 hours. After soaking, the shells were dried at 250°C for 10 minutes in an oven and then crushed into fine powder using a planetary ball milling machine which were then sieved through a 75 µm mesh. In this study 75µm and 45µm Soda-lime silica glass powder (GP) particle sizes were considered. GP was collected from local recycling plant and was mechanically sieved to obtain the 75µm particle size. The 45 µm GP particles were obtained by grinding 75µm GP in a planetary ball milling machine at a speed of 800 rpm for one hour.

Composite mortar specimens were prepared with GP and ESP as partial replacement of Portland limestone cement content by weight of 10% and 15%. With three different types of wastes (GP, treat ESP and untreated ESP) of constant particle size of 75 µm, 7 different mortar mixtures were designed as shown in details in Table 1. Portland limestone cement (CEM II/A-LL 42.5N) which conforms to EN 197-1:201, CEN standard sand and the different wastes were mixed in a mechanical mixer to obtain homogeneity in all mixtures. The mixtures were molded in layers in a jolting apparatus for 24 hours and then cured in water for 2, 7 and 28 days at 20°C. The mix proportions provided in table 1 is for one batch of mortar. Each batch yielded three specimens in the form of 40 mm × 40 mm × 160 mm prisms for the compressive strength test of the mortar.

TABLE 1. Mix proportions for the different mortar specimens (gram)

Mix Name	Portland limestone cement	Distilled water	CEN Standard sand	GP (75 µm)	Untreated ESP (75 µm)	Treated ESP (75 µm)
Control	450	225	1350	0	0	0
Treated ESP (10%)	405	225	1350	0	0	45
Treated ESP (15%)	382.5	225	1350	0	0	67.5
Untreated ESP (10%)	405	225	1350	0	45	0
Untreated ESP (15%)	382.5	225	1350	0	67.5	0
GP (10%)	405	225	1350	45	0	0
GP (15%)	382.5	225	1350	67.5	0	0

The fine and coarse aggregates were mixed homogeneously in a mixer for 20 s, followed by gradual addition of the mixing water over 30 s based on the water absorption rate of the different aggregates (2.4%, 2.8% and 3.4% for rocksand, Aggregates (6 - 10 mm) and Aggregates (10 - 20 mm) respectively). The mixture of aggregates was allowed to mix for another 30s to obtain a uniform moisture content throughout the mix. Cement (CEM II/A-LL 42.5N), eggshell particles and/or recycled glass were then added based on the design mix of the composite concrete and blended for one more minute. The remaining water and plasticiser CS800 were added, mixed for 3 minutes until a uniform mixture was achieved.

Table 2 shows the reference concrete design mix used in this study to maintain a constant slump test result of 140 ± 10 mm. The replacement of cement (10% and 20%) with eggshell particle and recycled glass was carried out based on the total binder mass (305kg/m3) and a total of six different mixtures were prepared with two different particle sizes (45 and 75 µm). Nine specimens (6 cubes and 3 cylinders) were casted from each mixture following the guideline set by BS EN 12390 standard for hardened-state property testing.

TABLE 2. Mix proportions for the reference concrete

Design Mix ID	Mix proportions of finished concrete (kg/m3)								Water to binder ratio
	Rocksand (0-4 mm)	Aggregates (6 - 10 mm)	Aggregates (10 - 20 mm)	Cement CEM II/A-LL 42.5N	CS800 Plasticiser	Eggshell powder (75 µm)	Glass powder (75 µm)	Glass powder (45 µm)	
Control	1205.4	392.3	571.9	305	1.22	0	0	0	0.57
10% ESP (75)	1205.4	392.3	571.9	274.5	1.22	30.5	0	0	0.57
10% GP (75)	1205.4	392.3	571.9	274.5	1.21	0	30.5	0	0.57
10 % GP (45)	1233.2	390.8	585.3	274.5	1.21	0	0	30.5	0.57
10% ESP (75) & GP (75)	1233.2	390.8	585.3	244	1.21	30.5	30.5	0	0.57
10% ESP (75) & GP (45)	1233.2	390.8	585.3	244	1.21	30.5	0	30.5	0.57

Test Procedure

Slump test:

A slump cone, positioned on a horizontal base plate, was filled with fresh concrete in three layers. Each layer was tamped 25 times with a standard tamping rod and the top of the cone was leveled with a trowel. After raising the cone carefully without any twisting motion, the slump was immediately measured by recording the difference in height between the cone and the displaced center of the concrete slump.

Testing of Mortar specimen:

The mortar prism specimens were removed 30 minutes before testing and the surfaces were cleaned to remove all excess moisture. All prism specimens were tested for flexural strength and the resultant half prisms were tested for compressive strength. With the prism specimens placed on the bending machine and supported by two rollers, a vertical load at a rate of 50N/s was applied at the centre until failure. Three samples for each design mix were tested at the age of 2, 7 and 28 days. The two half prisms resulted from the flexural test were used for compressive strength test following the guidelines set by standard BS EN 12390-3. With all surfaces cleaned, the specimens were centered on the lower platen increasing load at a rate of 2400 ± 200 N/s was applied perpendicular to the direction of casting until no further load can be sustained. The compressive strengths are calculated by dividing the average failure load of the half prisms at specified age by the loaded cross-sectional area (1600 mm^2).

Testing of Concrete specimen:

Concrete cube specimens of dimensions 150 x 150 x 150 mm were used to perform the compressive strength test at 7 and 28 days. Similarly, the specimens were positioned between the two platen of the compressive machine and were crushed on their sides by applying a steady load until facture. Three samples of each design mix were tested and the compressive strength were calculated by dividing the average failure load by the cross-sectional area of the cube (22, 500 mm^2).

The cylindrical specimens (150 mm diameter and 300 mm depth) conforming to EN 12390-1 were used to conduct the tensile splitting strength test as per the standard BS EN 12390-6. Cleaned specimens were centrally placed in the testing machine, and packing strips were added along the top and bottom of the loading plane. An increasing load at a constant rate was applied until failure and the maximum load was recorded. Split tensile strength tests were conducted at day 28 only.

RESULTS AND DISCUSSION

Compressive Strength of Mortar

The compressive strength test results for the different concentration of ESP and GP in mortar resulting to seven design mixes as a function of curing time are shown in figure. 1. It is noted that the addition of both ESP and GP in mortar as partial cement replacement has resulted to a lower compressive strength. This reduction in strength is due to lower content of cement present in the mix, which has also been reported by Ramasamy and Govindarajan [35]. Moreover, there were abundant sulfate ettringite in the mixture transforming into monosulfate [25]. This transformation is because all Calcium sulfate ($CaSO_4 \cdot 2H_2O$) has been used in the synthesis of ettringite [44]. The resulted monosulfate created internal stress, thus leading to loss of compressive strength at all stages. The loss was more significant when cement was partial replaced by 15% treated ESP.

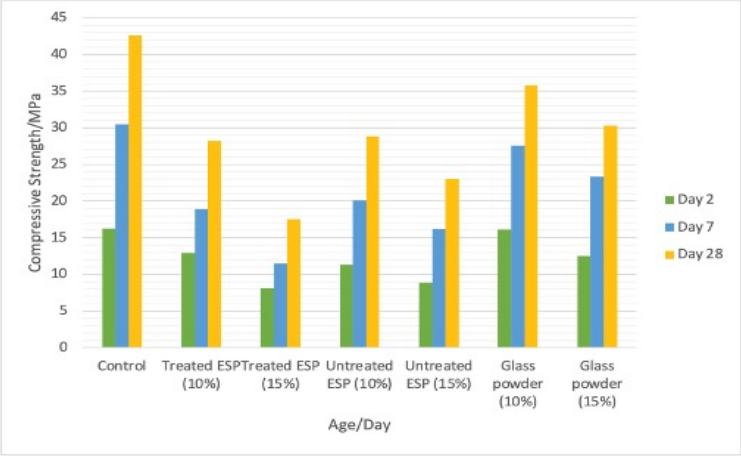

FIGURE 1. Compressive strength for Mortar with different concentration of ESP and GP

The performance of treated ES powder in the design mix was not significant. When cement was replaced by 10% with treated ESP, the compressive strength at 28 days did not improve as compared to the untreated ESP mortar. As the ratio of cement replacement is increased to 15%, the treated ESP mortar showed a lower strength than untreated ESP mortar of the same replacement ratio. It is clear that the treated ESP with 100% calcite $CaCO_3$ in the mixture did not improve the hydration process and the pozzolanic reaction. Thus, there is insufficient calcium oxide for the formation of primary and secondary calcium-silicate-hydrate (C-S-H) gel during the hydration process and pozzolanic activity. However, the treated ESP concrete exhibit high early compressive strength at 10% replacement ratio compared with untreated ESP specimens at early stage of curing.

A higher degree of secondary development of C-S-H gel is observed at an early age when the Portland limestone cement is replaced by 10% GP. However, as the curing period is increased, there is insufficient pozzolanic interaction with limestone Portland cement; where less hydration products were produced, resulting in inadequate development of C-S-H gel at later stages. The compressive results obtained for ESP and GP in mortar demonstrate that GP showed superior performance as a supplemental cementitious material as compared to ESP.

Workability of Concrete

All ESP and GP mixtures were compactable and did not show sign of segregation. Figure 2 shows GP has a more pronounced impact on decreasing workability as compared to ESP and the highest reduction is recorded when GP

particles are reduced to 45 µm and failed to meet the acceptable range of 130–150 mm. This observation suggested that the smaller GP particle size necessitated a higher water demand during hydration. A reduction in availability of water compromises the ability to facilitate smooth particle flow within the mix [45]. Moreover, a reduction in the finesse modulus of the cementitious material would lead to lower amount of cement paste available in the mix, thus reducing the lubricating effects per unit surface area of the aggregate. Superplasticizers are recommended to improve the workability and consistency of the mixture [37]. However, when 10% ESP (75 µm) is added with 10% GP (75 µm) for partial replacement of cement by 20%, the slump value is lower than the mixture 10% ESP (75 µm) & 10% GP (45 µm). This is due to the difference in finesse modulus which may have contributed to a stiffer and less workable concrete mixture [45]. No change in the slump value was noted with the addition of 10% ESP(75) in the reference design mix, thus, indicating that 10% replacement of cement by ESP of particle size 75 µm did absorb water excessively, resulting to similar water content as in the reference mix. However, reducing the particle size of ESP will increase the water absorption as a result of larger surface area, hence reducing the workability of the concrete mix [46].

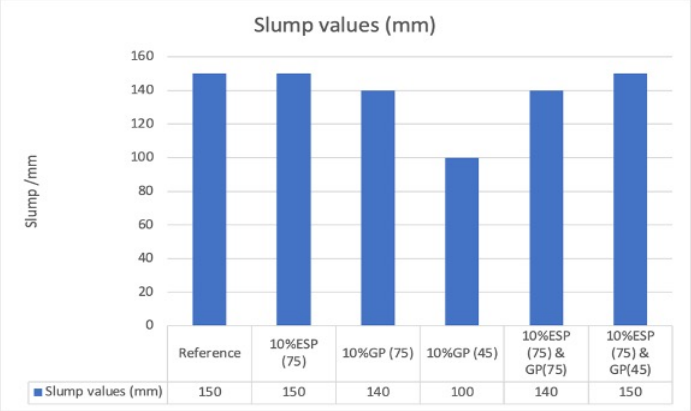

FIGURE 2. Workability of the different concrete mixtures

Compressive Strength of Concrete

The control mix design has compressive strength of 40.7 MPa at 28 days. When cement in the reference mix is partially replaced by 10% GP (75 µm), the compressive strength is reduced to 28.8 MPa. However, when reducing the GP particle size to (45 µm), the compressive strength is increased to 43.3 MPa as illustrated in figure. 3. Thus, finer GP particle has a better pozzolanic activity with the cement paste. The pozzolanic activity with Calcium Hydroxide improves the strength of concrete through the formation of hydration compound Calcium silicate Hydrate (C–S–H). Moreover, with finer GP particles, the concrete is more densely packed as the powder fills up the existing voids for the development for higher compressive strength.

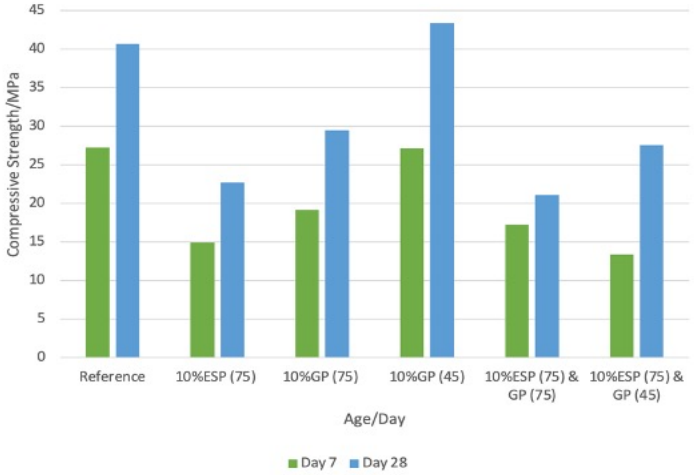

FIGURE 3. Compressive strength of concrete of different mix design for partial replacement of cement

Despite several researchers have reported an optimal ESP replacement of 10%, the strength is reduced to 22.7 MPa when substituting GP with ESP (75 μm). Therefore, it can be concluded that there was insufficient interaction between silica from the cement and calcium oxide from ESP under sustained moisture conditions for the formation of C-S-H gel [2]. A similar observation is noted when cement was replaced by 10% ESP (75 μm) and 10% GP (75 μm) as a result of lower cement content which has reduced the hydration products in the mix. A lower fineness modulus of the ESP and GP concrete composite has increased voids in the design mixtures which affects both porosity and compressive strength [45]. Reducing the particle size of GP from 75 μm to 45 μm in the design mix ESP-GP, the compressive strength is increasing to 276 MPa, representing an increase of 31%.

Split tensile Strength of Concrete

The Split tensile strength is reduced when the cement content is replaced by ESP and GP while statistical analysis of the samples confirmed significant differences in mean, indicating both composition and particle size impacted the split tensile strength. The strength for the mixture 10% ESP(75) & GP(45) is reduced by 24.3%, while 10% ESP(75) & GP(75) is decreased by 33.5%. Overall, 10% of GP represents the best partial replacement of cement as shown in figure 4 and the smaller the particle size, the higher split tensile strength [34]. The amorphous silica content in GP reacts with the free lime in cement to form hydrated products with binding properties to provide more strength [32]. Moreover, the pozzolanic activity of glass increases with GP particle smaller than 75 μm. Remarkably, the mixture 10%ESP(75) & 10% GP(45) and the mixture 10%ESP(75) exhibited nearly identical reduction in compressive strength. This result indicates that the pozzolanic activity of the 45 μm GP has contributed to additional binding property despite a significant amount of 20% cement replacement. Thus, fine GP can be considered as supplementary cementing material.

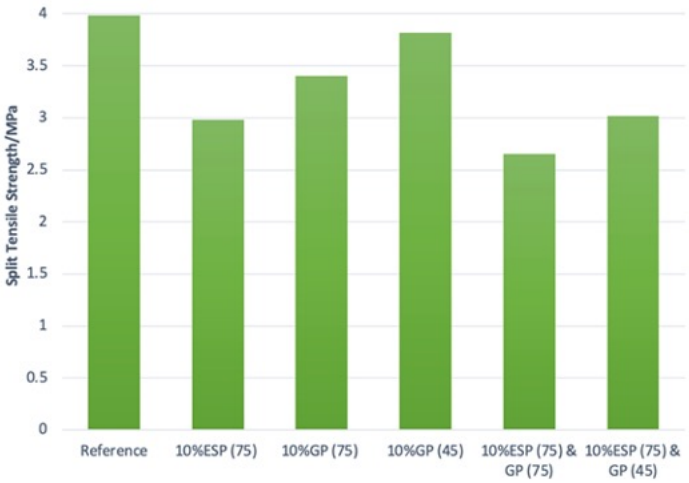

FIGURE 4. Split tensile strength of concrete mixtures at 28 days

CONCLUSION

The growing problem of waste generation has made effective waste management a critical priority. This is especially of significant interest in the construction industry, where recycling waste products is becoming an increasingly attractive option for the production of new sustainable building materials. This study explored the potential of using two specific waste streams, ESP and GP, as partial replacements for cement in concrete and the applicability of combining ESP with GP, using two different GP particle sizes. The experiments were primarily designed to reveal the relative benefits and drawbacks of incorporating these waste materials into concrete. The results showed that the addition of treated ES powder to the mortar mix didn't significantly affect its performance. The treated ES powder contained 100% calcite ($CaCO_3$), which doesn't provide enough calcium oxide (CaO) for the formation of C-S-H gel which is crucial for strength development. All ESP-GP specimens have a lower compressive strength as compared to the control design mix. The 20% cement replacement in the GP-ESP mixture has reduced the compressive strength to 21.1MPa at 28 days. To mitigate this shortcoming, ESP and GP of particle size smaller than 45 μm should be introduced in the mixture in order to induce reaction with the calcium hydroxide byproduct of cement

hydration to form additional cementitious material. Moreover, the smaller particles produce micro filler action in concrete, thus leading to a denser and stronger concrete matrix. As demonstrated in this study, reducing the GP particle size to 45 μm in the ESP-GP mixture, the compressive strength is increased by 30%. Hence, to maximize the use of two waste products as effective supplementary cementitious material for better economic and environmental advantages, it is recommended that future studies investigate the influence of ESP-GP of smaller particle size in concrete with various replacement ratio.

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