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CHICKEN EGGSHELL WASTE POWDER AS A PARTIAL REPLACEMENT FOR FLY ASH IN GEOPOLYMER CONCRETE

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Abstract — This study investigates the compressive strength of geopolymer concrete incorporating chicken eggshell powder as a partial replacement for fly ash. The objective is to evaluate the impact of eggshell powder on the properties of geopolymer concrete, specifically its slump value, specific gravity, and compressive strength. The experimental procedure utilized concrete designed for a 25 MPa strength, producing 45 cylindrical specimens measuring 10 cm in diameter and 20 cm in height. The specimens were cured in an oven at a constant temperature of 60°C for 4 hours. Thereafter, they were stored under ambient conditions for 1 day and then immersed in a water-curing tank until one day prior to the designated testing age. Compressive strength tests were conducted at curing ages of 7, 14, and 28 days. The findings indicate that a 10% substitution of chicken eggshell powder yields optimal results, achieving a compressive strength of 25.25 MPa—slightly above the target strength by 1%. As the substitution level increased, the slump value declined, ranging from 6 cm at 0% eggshell powder to 2 cm at 25%. The highest specific gravity was recorded at 10% substitution (2409.55 kg/m³), while the lowest was 2251.59 kg/m³. The maximum compressive strength was observed at 10% substitution after 28 days, showing a 12.77% improvement compared to the control sample. Conversely, increasing the substitution beyond 10% led to a significant reduction in compressive strength, with a 34.18% drop at 25% substitution. The findings demonstrate that chicken eggshell waste can be effectively utilized as a sustainable supplementary precursor in geopolymer concrete. The optimum substitution level of 10% not only improved compressive strength but also provides an environmentally beneficial pathway for reducing agricultural waste disposal and decreasing reliance on conventional industrial materials in sustainable construction.

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***Keywords*:** compressive strength, concrete, eggshell powder, fly ash, geopolymer

1.0 INTRODUCTION

The development of the construction industry sector generally also influences socio-economic development in a country. The construction industry continues to depend on reinforced concrete [1], a material that is widely favoured for its accessibility, versatility, and long-lasting performance [2]. However, the rapid growth of the cement industry as the main ingredient in reinforced concrete contributes significantly to high greenhouse gas emissions, especially due to high CO_2 emissions. Carbon dioxide (CO_2) is the primary constituent of greenhouse gases (GHG) and is recognised as a major contributor to global warming and climate change. The effects of global warming are anticipated to persist into the future. Based on data from the Ministry of Industry, total GHG emissions reached 238.1 million tonnes in 2022, 6.82% above the previous year. Of the 238.1 million tonnes, the largest contributor to emissions was 152.2 million tonnes of CO_{2e} (64% of total industrial GHG emissions). This number increased quite significantly by 21.66% from the figure in 2021 [4].

Based on this condition, significant efforts are needed to reduce GHG emissions, including by introducing more environmentally friendly construction materials. In the cement industry sector, several efforts have been initiated to produce more environmentally friendly cement, such as Portland Composite Cement (PCC) and Portland Pozzolan Cement (PPC). This type of cement has a lower clinker content than Type I Portland Cement, so it produces fewer CO2 emissions. Another alternative is to completely replace cement in concrete production, up to 100%. This form of concrete, known as geopolymer concrete, uses fly ash as a cement substitute. Geopolymer concrete has become a significant advancement in the construction sector, presenting a viable alternative to traditional Portland cement concrete [5-7]. Geopolymer concrete utilizes materials such as fly ash that are rich in silica and aluminium, which are activated by an alkaline solution to form the binder. This process allows the formation of concrete without the presence of Portland Cement, paving the way for more environmentally friendly

construction solutions. The function of water as a cement reagent in normal concrete is replaced by an activator solution, consisting of a chemical mixture of NaOH (caustic soda) and Na_2SiO_3 (water glass). Recent developments in geopolymer concrete research involve the use of innovative admixtures or the addition of waste materials such as rice husk ash [8], titanium dioxide [9], coffee grounds [10], and ceramic waste powder [11].

Chicken eggshells, a waste product of the rapidly growing livestock industry in Indonesia, can be utilised in the production of geopolymer concrete. Based on the Indonesian Statistical Center Bureau, data show that chicken egg production in Banten reached 265,716.30 tonnes in 2023. Chicken eggshell waste holds potential as a component in concrete mixtures. According to Moison et al., geopolymer concrete created by combining eggshell powder and fly ash can be applied in road pavement construction [12]. Shekhawat et al. [13] used chicken eggshell powder as a partial substitute in fly ash-based geopolymers. Eggshells contain high CaO (58.89%), which can function as a binding material in concrete mixtures [13]. They found that the calcium content in eggshells can contribute to increased compressive strength of concrete, providing new insights into improving the mechanical properties of geopolymers. A geopolymer composite comprising 50% eggshell powder and 50% fly ash, with an activator ratio of 2, was identified as optimal for both unconfined compressive strength and split tensile strength. Incorporating eggshell powder as a partial cement replacement can enhance concrete strength by as much as 20%.

This research investigates the impact of incorporating chicken eggshell powder as a partial replacement for fly ash. The substitution levels range from 0% to 25% of the fly ash weight. The eggshells used are sourced from food waste, while the fly ash is obtained from the Suralaya steam power plant in Indonesia. Although numerous studies have investigated the incorporation of eggshell waste in cement-based materials, limited research has evaluated the behaviour of high-calcium eggshell powder as a partial replacement for fly ash in geopolymer concrete produced using locally sourced Indonesian materials. Given that eggshell powder contains approximately 97% CaO, its incorporation may contribute to the formation of additional calcium-aluminosilicate-hydrate (C-A-S-H) gel alongside conventional sodium-aluminosilicate-hydrate (N-A-S-H) gel, potentially enhancing matrix densification and compressive strength. Therefore, this study investigates the optimum replacement level of fly ash with eggshell powder and evaluates its effect on fresh and hardened geopolymer concrete properties.

2.0 MATERIALS AND METHODS

All experimental procedures were conducted at the PT Jaya Beton Indonesia laboratory, following the guidelines of the Indonesian National Standard (SNI). The testing of material properties, including fine and coarse aggregates, was carried out in accordance with SNI regulations. Table 1 presents the physical characteristics of the fine and coarse aggregates, while Figure 1 displays the results of their gradation tests. As illustrated in Figure 1, the aggregate particle sizes fall within the acceptable range defined by ASTM C33/C33M-18, the Standard Specification for Concrete Aggregates [14].

Table 1. Physical Properties of Aggregate

Physical Properties	Coarse Agg.	Fine Agg.
Bulk Specific Gravity	2.55	2.52
Unit weight (Mg/m^3)	1.46	1.46
Fines content (%)	0.89	3.22
Absorption (%)	2.81	2.86
Abrasion (%)	20.67	-
Fineness Modulus	7.78	3.11

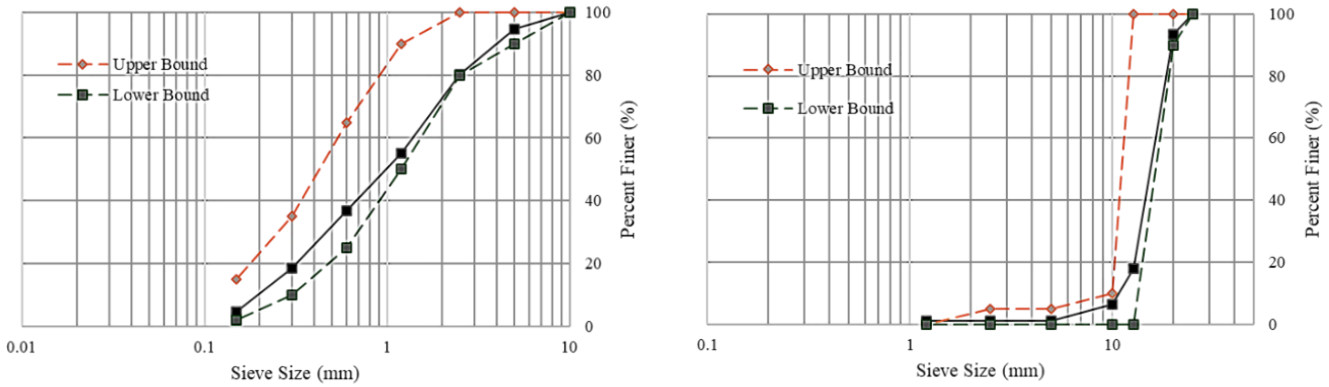


Figure 1 Gradation curve for fine and coarse aggregate

The eggshells used in this study were obtained from food waste in the Sawah Baru area, Ciputat, Indonesia. The eggshells were first thoroughly washed (Figure 2a), then oven-dried at 110°C for 24 hours (Figure 2b), and finally ground into powder using a blender (Figure 2c). Only eggshell powder with particles smaller than 0.150 using a mesh sieve no. 100 mm was used in this study.



(a) (b) (c)

Figure 2 Processing eggshells into powder

Meanwhile, to determine the chemical content of the chicken shell powder used, an XRF (X-ray Fluorescence) test was carried out. The chemical compound content in chicken shells is shown in Table 2. The test results using XRF show that chicken eggshell powder contains a high Ca content (97.49%) in the form of CaO (97.3%). Calcium oxide (CaO) is a material that can be used to increase compressive strength in making concrete using cement or fly ash. Because type F fly ash has a low CaO content, it is necessary to add calcium oxide (CaO), because CaO is needed in the process of making concrete and is able to increase the compressive strength of concrete [15].

Table 2. Chemical Composition of Eggshell Powder

Element	(%)	Compound	(%)
Ca	97.497	CaO	97.308
Ag	0.801	Al_2O_3	0.804
Ag	0.629	Ag_2O	0.657
In	0.43	SiO_2	0.552
In	0.315	In_2O_3	0.381
Si	0.302	Fe_2O_3	0.268
Fe	0.287	MnO	0.05
Sr	0.063	SrO	0.048
Mn	0.059	Cr_2O_3	0.034
Al	0.0496	BaO	0.015
Sr	0.041	ZrO_2	0.001

The targeted compressive strength value of the concrete test specimen is f_c' = 25 MPa with a percentage of chicken eggshell powder of 10%, 15%, 20%, and 25%. The variation code for chicken eggshell powder as a partial substitute for fly ash is GCESP 0, GCESP 10, GCESP 15, GCESP 20, and GCESP 25. In this mixture, the ratio of fly ash and alkali activator is taken as 2:1, while the ratio of Na_2SiO_3 to NaOH is 3:1. NaOH solution is produced from the dissolution of solid sodium hydroxide in water, with a solution molarity of 8.0. Table 3 presents the material composition of the geopolymer concrete mixture.

Table 3 Composition of Geopolymer Concrete Mixture

Code	Fly Ash Content (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Eggshell Powder (kg/m^3)	NaOH (kg/m^3)	Na_2SiO_3 (kg/m^3)	Water (kg/m^3)
GCESP 0	362.33	590.32	1166.75	0.00	10.19	161.93	33.74
GCESP 10	326.10	590.32	1166.75	36.23	10.19	161.93	33.74
GCESP 15	307.98	590.32	1166.75	54.35	10.19	161.93	33.74
GCESP 20	289.86	590.32	1166.75	72.47	10.19	161.93	33.74
GCESP 25	271.75	590.32	1166.75	90.58	10.19	161.93	33.74

After casting, all specimens were compacted using a vibrating table to reduce entrapped air and ensure proper consolidation. The specimens remained in the moulds for 24 hours before demoulding. After 24 hours, the specimens were cured in an oven at a constant temperature of 60°C for 4 hours. Thereafter, they were stored under ambient conditions for 1 day and then immersed in a water-curing tank until one day prior to the designated testing age. The specimens were tested at 7, 14, and 28 days. A total of 45 cylindrical specimens with dimensions of 100 mm × 200 mm were prepared, consisting of three replicate specimens for each mixture and testing age. Compressive strength testing was conducted according to ASTM C39/C39M, while slump testing was performed following the applicable concrete testing procedures. This curing procedure was consistently applied throughout the experimental programme.

Compressive strength testing was conducted when the specimens reached 7, 14, and 28 days of age, in accordance with the ASTM C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [16]. The compressive strength of the specimens can be calculated using the following equation:

$$f_c = \frac{P}{A} \tag{1}$$

Where f_c is the concrete compressive strength (in MPa), P is the maximum load, and A is the cross-section of the specimen (in mm).

In addition to testing compressive strength, the density of the specimens was determined by measuring their mass (kg) and volume (mm^3). The density of the specimen can be calculated using the following equation:

$$\rho = \frac{m}{V} \tag{2}$$

3.0 RESULTS AND DISCUSSION

3.1. Slump Test

A slump test was performed on the concrete mixture before pouring it into the cylindrical mould. The aim of the slump test was to assess the workability of the geopolymer concrete. As indicated by the results of the slump test (Figure 3), an increase in the percentage of eggshell powder affects the slump value of the geopolymer concrete mixture, leading to a decrease in its measured value. The use of 10% eggshell powder in GCESP 10 showed a decrease in the slump value of 16.67%. The slump value continued to decrease in the GCESP 15 and GCESP 20 mixtures by 25%. A decrease in the slump value of 33.33% occurred in the GCESP 25 mixture, which used 25% eggshell powder. In this study, eggshells were ground to a size smaller than 0.150 mm to replace the role of fly ash in the geopolymerisation reaction. However, the finer size of the eggshell powder is finer than the fine aggregate (sand) size; it turns out that it requires more water or activator. The greater the volume of eggshell powder in the mixture, the stiffer the concrete mixture becomes [17]. According to Hakeem et al. [18], incorporating eggshells

during the casting process leads to significant water absorption, which subsequently decreases the workability of the concrete mixture. This is also in line with the research of Sulaiman et al. [19] and Kuo et al. [20].

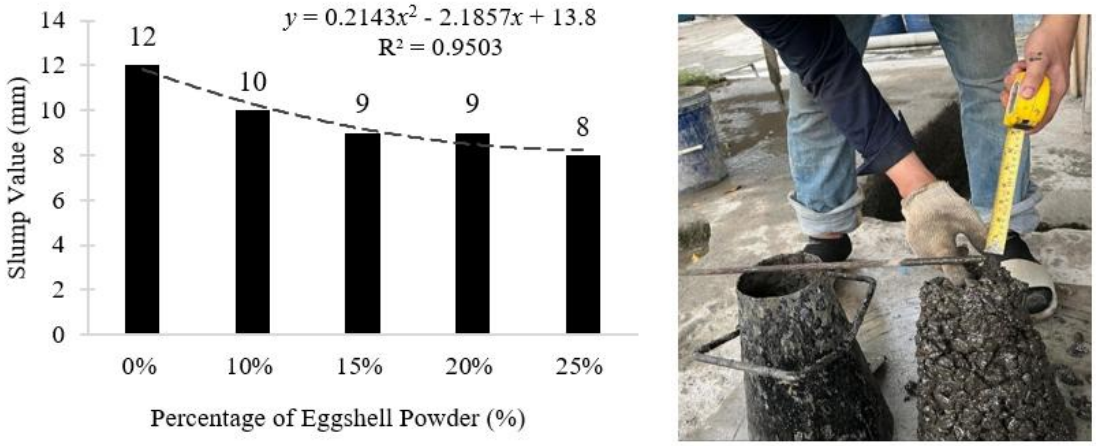


Figure 3 Slump test results

3.2. Concrete Unit Weight

Before the compressive strength test is carried out, the concrete must first undergo a weighing process. This weighing is carried out to obtain information about the density of the concrete to be used. From the average weight of geopolymer concrete, the eggshell powder is obtained. To find out the growth of the specific gravity of each composition of eggshell powder, it can be seen in Figure 4.

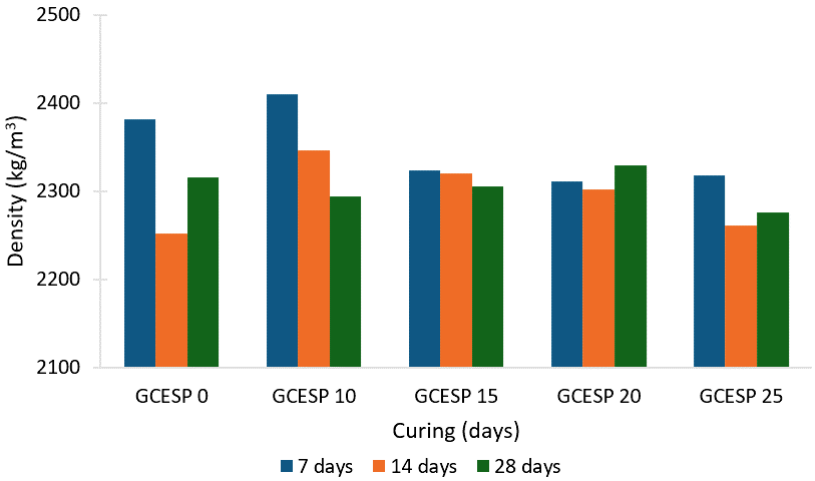


Figure 4 Slump test results

Figure 4 presents the density values of geopolymer concrete containing various proportions of eggshell powder (GCESP 0 to GCESP 25) at curing ages of 7, 14, and 28 days. The measured density ranged from 2251.59 kg/m³ to 2409.55 kg/m³, indicating that all mixtures can be classified as normal-weight concrete. The highest density was observed in the GCESP 10 mixture, reaching 2409.55 kg/m³ at 7 days, whereas the lowest density was recorded in the control mixture at 14 days with a value of 2251.59 kg/m³. Overall, the results indicate that incorporating eggshell powder at a limited replacement level can improve the compactness of the geopolymer concrete matrix.

The increase in density observed in GCESP 10 may be attributed to the high calcium oxide (CaO) content of the eggshell powder, which reached 97.31% according to the XRF results. The finely ground eggshell particles acted as micro-fillers capable of occupying voids between fly ash particles and aggregates, resulting in improved particle packing and a denser matrix structure. In geopolymer systems, calcium-rich materials may also contribute to the formation of additional calcium-containing reaction products, such as calcium-aluminosilicate-hydrate (C-A-S-H) gel, which can reduce pore volume and improve the overall compactness of the binder matrix. Similar observations were reported by Handana et al. (2024), who found that incorporating eggshell powder into geopolymer mixtures

enhanced matrix densification and contributed to higher compressive strength through the formation of calcium-based reaction products. [5]

However, when the eggshell powder content exceeded 10%, the density tended to decrease. This behaviour suggests that excessive replacement of fly ash reduced the availability of reactive silica and alumina required for geopolymerisation. Although eggshell powder supplies calcium, it contains only limited amounts of aluminosilicate compounds compared to fly ash. Consequently, higher replacement levels may reduce the production of geopolymeric gel and increase the amount of unreacted particles within the matrix. A similar trend was reported by Abdellatief et al. [7], who observed that geopolymer mixtures containing more than 10% eggshell powder exhibited reduced performance due to disruption of the precursor balance and lower efficiency of geopolymer reactions. [7]

Furthermore, the density values obtained in this study are consistent with previous investigations on eggshell-based geopolymer materials. Experimental studies on geopolymer composites incorporating eggshell powder have shown that moderate additions of eggshell waste improve packing density and decrease internal porosity, whereas excessive dosages lead to a less homogeneous microstructure and lower density values. Therefore, the results suggest that a 10% eggshell powder substitution represents the optimum level for achieving a dense geopolymer concrete matrix while maintaining sufficient fly ash content to sustain effective geopolymerisation reactions [6, 22].

3.3 Compressive Strength Test

The compressive strength results were obtained from testing cylindrical specimens. The researchers made five variations of the mixture composition with different percentages of chicken eggshell powder, resulting in a total of 45 specimen samples used in this study. Compressive strength testing was carried out at three different times, namely when the concrete was 7, 14, and 28 days old.

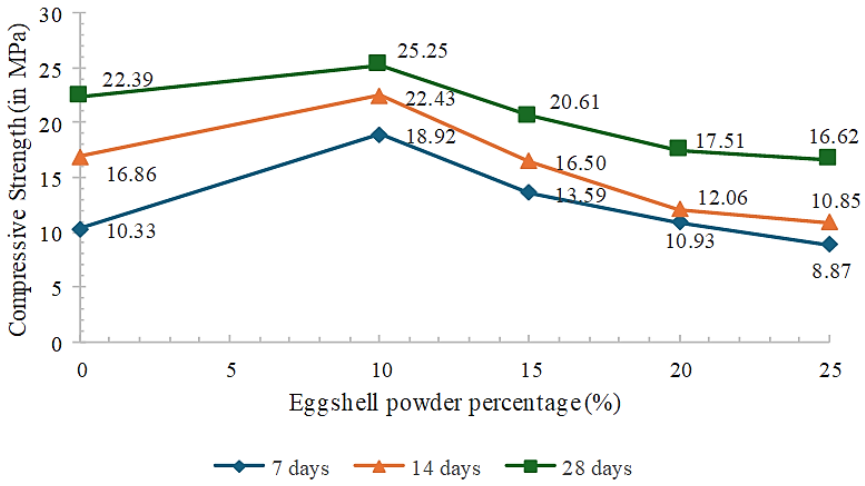


Figure 5 Compressive strength of concrete

Figure 5 illustrates the compressive strength development of geopolymer concrete containing different proportions of eggshell powder (GCESP 0 to GCESP 25) at curing ages of 7, 14, and 28 days. The results indicate that the incorporation of eggshell powder significantly influenced the mechanical performance of the geopolymer concrete. Compressive strength increased with the addition of eggshell powder up to a substitution level of 10%, after which a continuous decline was observed. The highest compressive strength was achieved by GCESP 10 at the age of 28 days, reaching 25.25 MPa, which exceeded the target design strength of 25 MPa and represented a 12.77% improvement over the control mixture (GCESP 0).

The enhancement in compressive strength at the 10% replacement level can be attributed to the exceptionally high calcium oxide (CaO) content of the eggshell powder. Previous studies have shown that calcium-rich materials can accelerate geopolymer reaction kinetics and contribute to the formation of additional calcium-aluminosilicate-

hydrate (C-A-S-H) and calcium-silicate-hydrate (C-S-H) gels. These reaction products complement the conventional sodium-aluminosilicate-hydrate (N-A-S-H) gel formed in fly ash-based geopolymers, resulting in a denser and stronger binder matrix. Handana et al. reported that the incorporation of eggshell powder in geopolymer mixtures enhanced compressive strength through the formation of calcium-based reaction products and matrix densification. In addition, recent experimental investigations demonstrated that moderate eggshell powder additions improved geopolymer performance by refining pore structure and reducing internal voids [5, 6].

However, when the eggshell powder content exceeded 10%, compressive strength decreased significantly. The 15%, 20%, and 25% replacement levels produced compressive strengths of 20.61 MPa, 17.51 MPa, and 16.62 MPa, respectively. This reduction is likely associated with the gradual decrease in fly ash content, which reduced the availability of reactive silica (SiO_2) and alumina (Al_2O_3), the primary components required for effective geopolymerisation. Although eggshell powder provides a substantial amount of CaO, it contains limited aluminosilicate constituents compared with fly ash. Consequently, excessive substitution may disrupt the balance between calcium and aluminosilicate phases, leading to incomplete geopolymer formation and lower strength development. Similar findings were reported by Abdellatief et al., who observed that geopolymer mixtures containing more than 10% eggshell powder exhibited reduced compressive strength due to the dilution of reactive geopolymer precursors [7].

The observed trend is also consistent with the study conducted by Yavuz, who reported that eggshell powder can improve geopolymer strength when used at an optimum dosage, whereas excessive incorporation may adversely affect matrix homogeneity and mechanical performance. Overall, the results indicate that a 10% eggshell powder substitution provides the most favourable balance between calcium enhancement and geopolymer precursor availability, resulting in optimum compressive strength development [22]. With the addition of 4% eggshell powder, the compressive strength of normal concrete shows an increase of 4.12% compared to concrete without eggshell powder [21].

Using chicken eggshell powder in concrete not only reduces waste sustainably but also produces more environmentally friendly construction materials and opens up the potential for sustainable development innovation.

4.0 CONCLUSION

Partial substitution of 10% in geopolymer concrete provides the most optimal results in increasing the compressive strength of concrete. The compressive strength value of the concrete is 25.25 MPa, an increase of 1% from the targeted f'_c, i.e., 25 MPa. The slump value tends to decrease as the percentage of eggshell powder increases. The specific gravity of geopolymer concrete in the study had the largest average density of 2409.55 kg/cm^3 at a percentage of 10% and the smallest density of 2251.59 kg/cm^3, with an average density of 2.31623 kg/cm^3. The largest compressive strength of geopolymer concrete is a result of 25.25 MPa in 28-day-old concrete with a percentage of 10%. The compressive strength of geopolymer concrete with partial substitution of chicken eggshells increased by 12.77% from 0% to 10%. The increase in the percentage of chicken eggshell powder from 10% to 25% decreased the compressive strength by 34.18%.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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