Jordan Journal of Civil Engineering, Volume **18**, No. **2**, **2024**
DOI: https://doi.org/10.14525/JJCE.v18i2.12

Jordan Journal of Civil Engineering

Journal homepage: https://jjce.just.edu.jo

Synthesis of Eggshell Powder and GGBS Geopolymer Designed by the Taguchi Method

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ARTICLE INFO

Article History:
Received: 29/6/2022
Accepted: 19/3/2024

ABSTRACT

This research endeavors to develop a geopolymer mortar synthesized from eggshell powder and ground granulated blast-furnace slag, utilizing the Taguchi L25 optimization technique to refine the synthesis process across molarity (A), precursor ratio (B) and curing duration (C). Analyzed at five distinct levels across 25 experimental setups, denoted as A1B1C1 through A5B5C5, these variables were rigorously tested. Compressive-strength measurement was employed as a criterion to assess the performance of three samples from each setup, alongside setting-time evaluation to ascertain the geopolymer concrete's workability. Optimal results were observed with a 60% eggshell to 40% slag ratio (A5B1C5), yielding the highest average compressive strength of 49.5 MPa after a curing period of 56 days. Conversely, a mix comprising 100% eggshell (A2B5C1) manifested the lowest compressive strength of 5 MPa at a 3-day curing period. Taguchi's signal-to-noise ratio analysis pinpointed the precursor ratio as a crucial determinant of compressive strength. Additionally, setting-time investigations revealed A5B1C5 as exhibiting the most advantageous initial and final setting times of 15 minutes and 30 minutes, respectively, compared to the protracted durations of 240 minutes and 540 minutes for A2B5C1. Through comprehensive chemical, micro-structural and mineralogical characterizations *via* X-ray fluorescence, Scanning Electron Microscopy (SEM) and X-ray diffraction, it was found that an increased proportion of ground granulated blast-furnace slag relative to eggshell enhances surface smoothness and density, indicative of successful polymerization. This was further corroborated by X-ray diffraction, which confirmed the formation of sodium alumina-silicate hydrate, calcium aluminum silicate hydrate and calcium silicate hydrate gels. Consequently, the study substantiates the potential of employing eggshell powder and ground granulated blast-furnace slag in the sustainable fabrication of geopolymers from waste materials.

Keywords: Geopolymers, GGBFS, Eggshell, Taguchi Method, Compressive strength.

INTRODUCTION

Mortars based on ordinary Portland cement (OPC) are employed in the construction and building industry and have attracted significant environmental concern (Kavya et al., 2022; Mathew and Sureshbabu, 2021). OPC production is highly energy-intensive, with significant amounts of carbon dioxide, a greenhouse gas emitted into the environment (Cadavid et al., 2020; Mehta et al., 2017). It has been reported that Portland-cement plants emit up to 1.5 billion tons of CO_2 annually, accounting for approximately 5% of the total CO_2 emissions in the atmosphere (Alberto and Guerreiro, 2021; Di Filippo et al., 2019). Therefore, attempts have been made to develop substitute materials that can partially or entirely replace the commonly-used cement binder.

Geopolymers hold promise as replacements for OPC, presenting a solution for reducing carbon emissions. Geopolymer concrete is derived from pozzolanic materials mixed with an alkaline solution in a polymer framework of tetrahedral-bonded SiO_4 and AlO_4 (Davidovits, 2013; Glukhovsky, 1959). Typically, pozzolanic materials are produced from sustainable and waste materials, such as fly ash, metakaolin, palm-oil fuel ash, rice husk, ground granulated blast-furnace slag (GGBS) and volcanic ash (Mathew and Sureshbabu, 2021; Rama and Shanthi, 2023). In this study, GGBFS and eggshell wastes are proposed because of their potential for application as the primary precursor in the manufacture of geopolymer mortars (Ganeshan and Venkataraman, 2022). GGBFS is a waste or residue product from large kiln combustion, whereas eggshell powder is a waste product from farms and chicken coops, obtained by grinding dried eggshells (Amu et al., 2005; Eldhose and Sasi, 2015; Pliya and Cree, 2015). GGBFS is a by-product of iron production in a blast furnace that predominately consists of molten calcium silicate and alumino-silicate (El-Chabib, 2020). Eggshell waste originates from places, such as chicken farms, bakeries, fast-food places, restaurants and homes. Several studies have reported its utility, attributed to its calcium-rich composition (Bhartiya and Dubey, 2018; Ngayakamo et al., 2020). These properties and sustainable resources emphasize the advantages of these materials and highlights the importance of this study.

Based on the abovementioned potential solution, an alternative for overcoming the aforementioned problems was proposed, i.e., utilizing GGBFS and eggshell waste as the primary materials for making geopolymers to reduce OPC usage. The raw materials were characterized using a particle-size analyzer and X-ray fluorescence (XRF) analysis to determine the particle-size distributions and chemical components, respectively. This research employed the Taguchi method for statistical analysis to discover the optimum geopolymer mixtures (Onoue et al., 2019). This method is highly effective, simple and easy to apply. Taguchi divided the factors that quantitatively affect geopolymers and in this research, the influencing factors are molarity, precursor ratio and curing duration. The compressive strength of each factor was tested to discover the optimum factor combination and the combination that achieves the highest and lowest compressive-strength results will be adopted for the setting-time test. Additionally, to identify the optimal parametric combination for the factors considered, signal-to-noise (S/N) ratios were calculated. Furthermore, the raw materials and optimum geopolymer mortar mixture after the compressive-strength test were characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses.

MATERIALS AND METHODS

The precursor materials for preparing the geopolymers were eggshell powder obtained from poultry waste products produced by eggshell milling and GGBFS obtained from the Krakatau Semen Indonesia Company. Figure 1 depicts the size distribution of the eggshell and GGBFS particles. Eighty percent of the eggshell particles were fine, having sizes smaller than 10 μm. The particle size of the precursor material affects the overall geopolymerization reactivity, because relatively fine particles afford a relatively large surface area for a reaction to occur (Kumar et al., 2015; Somna et al., 2011). Further, GGBFS particles have a size of less than 1000 μm and demonstrate good fineness; however, the lowest limit of the GGBFS-particle size is constrained to 100 μm from the best standpoint. Therefore, both raw elements are reactive precursor materials.

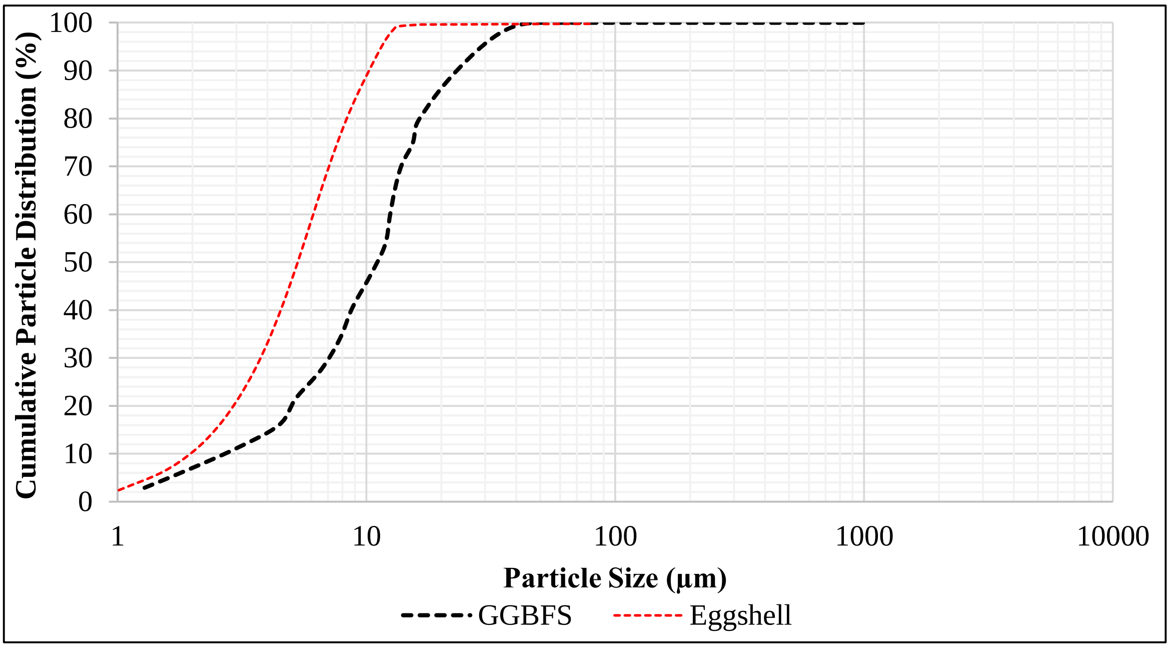

Figure (1): Particle-size distribution of the eggshell and GGBFS

Table 1. XRF results of the eggshell and GGBFS

Chemical Constituents (% by weight)	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**K_2O**	**SO_3**	**Na_2O**	**MgO**	**LOI[1]**	**Specific gravity**
Eggshell	0.79	0.66	0.45	61.37	1.54	2.81	-	0.44	28.04	2.35
GGBFS[2]	34.18	12.54	1.88	37.77	0.48	0.25	0.67	9.84	-	2.81

[1] Loss on Ignition.

[2] Ground Granulated Blast-furnace Slag.

XRF analysis was performed on these materials and the results are shown in Table 1. The eggshell specimen was composed of 61.37 mass% CaO, 2.81 mass% SO_3 and 1.54 mass% K_2O. In contrast, the primary constituents of GGBFS were 37.7% CaO, 34.18 mass% SiO_2, 12.54% Al_2O_3, 9.84 mass% MgO and 1.88% Fe_2O_3. The eggshell and GGBFS predecessors were deemed to have specific gravities of 2.35 and 2.81, respectively. The alkaline activator solution used was a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The analytical-grade NaOH was in pellet form, with a density of 1.00 g/cm^3 and 98% purity, whereas Na_2SiO_3 was in liquid form, with a density of 1.35g/cm^3 and pH 11.1. Meanwhile, sand was used as a fine aggregate with a maximum grain dimension of 4.76 mm with water. The method employed for the production of the geopolymers was the Taguchi design with three factors: molarity (M) of NaOH (A), precursor ratio (eggshell:GGBFS) (B) and curing duration (C), which are shown in Table 2. Each factor combination is listed using the Taguchi L25 method, as shown in Table 3.

Table 2. Level of each factor in Taguchi's design

Factor	**Unit**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
A: Molarity	M	8	10	12	14	16
B: Precursor ratio	%	60:40	70:30	80:20	90:10	100:0
C: Curing duration	D	3	7	14	28	56

Table 3. Orthogonal arrays of the Taguchi method [L25(5*5)]

Trial	Factor A	Factor B	Factor C
T1	1	1	1
T2	1	2	2
T3	1	3	3
T4	1	4	4
T5	1	5	5
T6	2	1	2
T7	2	2	3
T8	2	3	4
T9	2	4	5
T10	2	5	1
T11	3	1	3
T12	3	2	4
T13	3	3	5
T14	3	4	1
T15	3	5	2
T16	4	1	4
T17	4	2	5
T18	4	3	1
T19	4	4	2
T20	4	5	3
T21	5	1	5
T22	5	2	1
T23	5	3	2
T24	5	4	3
T25	5	5	4

Table 4. Mixture design of a geopolymer using the Taguchi method

Trial	Eggshell Powder	GGBFS[1]	Na_2SiO_3	NaOH	Water	Sand
T1	66.3228	44.2152	43.426	5.696	17.8	165.806
T2	77.3766	33.1614	43.426	5.696	17.8	165.806
T3	88.4304	22.1076	43.426	5.696	17.8	165.806
T4	99.4842	11.0538	43.426	5.696	17.8	165.806
T5	110.538	0	43.426	5.696	17.8	165.806
T6	66.3228	44.2152	43.426	7.12	17.8	165.806
T7	77.3766	33.1614	43.426	7.12	17.8	165.806
T8	88.4304	22.1076	43.426	7.12	17.8	165.806
T9	99.4842	11.0538	43.426	7.12	17.8	165.806
T10	110.538	0	43.426	7.12	17.8	165.806
T11	66.3228	44.2152	43.426	8.544	17.8	165.806
T12	77.3766	33.1614	43.426	8.544	17.8	165.806
T13	88.4304	22.1076	43.426	8.544	17.8	165.806
T14	99.4842	11.0538	43.426	8.544	17.8	165.806
T15	110.538	0	43.426	8.544	17.8	165.806
T16	66.3228	44.2152	43.426	9.968	17.8	165.806
T17	77.3766	33.1614	43.426	9.968	17.8	165.806
T18	88.4304	22.1076	43.426	9.968	17.8	165.806
T19	99.4842	11.0538	43.426	9.968	17.8	165.806
T20	110.538	0	43.426	9.968	17.8	165.806
T21	66.3228	44.2152	43.426	11.392	17.8	165.806
T22	77.3766	33.1614	43.426	11.392	17.8	165.806
T23	88.4304	22.1076	43.426	11.392	17.8	165.806
T24	99.4842	11.0538	43.426	11.392	17.8	165.806
T25	110.538	0	43.426	11.392	17.8	165.806

[1] Ground Granulated Blast-furnace Slag.

The mixing process includes the material-inspection stage involving the fine-aggregate sieve analysis (SNI 03 1968-1990), fineness-modulus (FM = 2.638) test with a medium FM classification (2.6 < FM < 2.9), specific gravity and water absorption of fine-aggregate tests (SNI 03 1970-1990), mud-content tests for the fine aggregate (SNI 03 4142-1996) and colorimetric tests (SNI 03 2816-2014). The mixture-planning stage and mixing quantities include mixing the eggshell powder, GGBFS and sand, along with an activator for various factor combinations, as listed in Table 4. The consistency test is conducted using the Vicat equipment in the laboratory, following the guidelines provided in the IS 4031 (Part 4)-1988. The penetration of the Vicat plunger ceases at a distance of approximately 5-7 mm prior to reaching the bottom surface. The determination of the beginning and final setting times was conducted in accordance with the guidelines outlined in IS: 4031 (Part 5)-1988, which necessitates the assessment of consistency.

Each factor combination produced three specimens in the form of a cube-shaped geopolymer mortar with dimensions of 5 × 5 × 5 cm. Each specimen was treated at room temperature with curing durations of 3, 7, 14, 28 and 56 days. The specimens were subjected to compressive-strength tests according to ASTM C109M and the results were compared to determine the optimum factor combination. The factor combinations that exhibited the highest and lowest compressive-strength results were utilized for the setting-time test using a Vicat needle (ASTM C187/C191, BS 4550 model NL 3012X/ 002). Additionally, the S/N-ratio analysis was carried out using the Minitab 18 software to determine the optimum factor combination from the Taguchi-method result. Furthermore, the mortar with the optimum compressive strength was characterized by SEM (Hitachi TM 3000) to analyze the microstructure morphology and XRD (Bruker D8 Advance) in order to identify the crystalline phase.

RESULTS AND DISCUSSION

This research tested the compressive strength of a geopolymer mortar, which was previously designed using the Taguchi method and the mortar with the optimum compressive strength was characterized by SEM and XRD. The geopolymer mortar produced in this research had various factor combinations of molarity, curing duration and precursor ratio of the eggshell and GGBFS. Table 5 shows the compressive strength from 25 trial mixtures for each geopolymer mortar specimen. The highest average compressive strength of 49.5 MPa was achieved with the A5B1C5 factor combination, whereas the lowest average compressive strength of 5 MPa was achieved with the A2B5C1 factor combination. A detailed discussion of the effect of each factor is given in the following sub-sections.

Table 5. compressive-strength results for each trial using the Taguchi method

Trial	Factor Combination	Specimen 1 (MPa*)	Specimen 2 (MPa*)	Specimen 3 (MPa*)	Average (MPa*)
T1	A1B1C1	20	16	16	17.3
T2	A1B2C2	32	24	32	29.3
T3	A1B3C3	16	12	12	13.3
T4	A1B4C4	4	8	4	5.3
T5	A1B5C5	9.2	11.6	12	10.9
T6	A2B1C2	40	40	36	38.7
T7	A2B2C3	32	32	36	33.3
T8	A2B3C4	24	20	12	18.7
T9	A2B4C5	16.4	28.8	19.6	21.6
T10	A2B5C1	5	5	5	5.0
T11	A3B1C3	12	36	32	26.7
T12	A3B2C4	12	20	24	18.7
T13	A3B3C5	24.8	29.2	23.2	25.7
T14	A3B4C1	8	5	8	7.0

T15	A3B5C2	16	12	12	13.3
T16	A4B1C4	44	40	28	37.3
T17	A4B2C5	40	47.2	44	43.7
T18	A4B3C1	8	16	16	13.3
T19	A4B4C2	16	16	12	14.7
T20	A4B5C3	8	8	8	8.0
T21	A5B1C5	55.2	51.6	41.6	49.5
T22	A5B2C1	16	16	12	14.7
T23	A5B3C2	20	24	20	21.3
T24	A5B4C3	16	12	12	13.3
T25	A5B5C4	12	8	5	8.3

* MegaPascal.

Compressive-strength Results Based on the Taguchi Method

Molarity

Figure 2 shows the compressive-strength results based on molarity. Evidently, the addition of A5 factors resulted in the highest compressive strength of 55.2 MPa produced at 16 M for specimen 1. Conversely, the lowest compressive strength of 4 MPa for specimen 1 was achieved at 8 M. Furthermore, the increase in the molarity from 8 M to 16 M increased the overall compressive strength for each specimen.

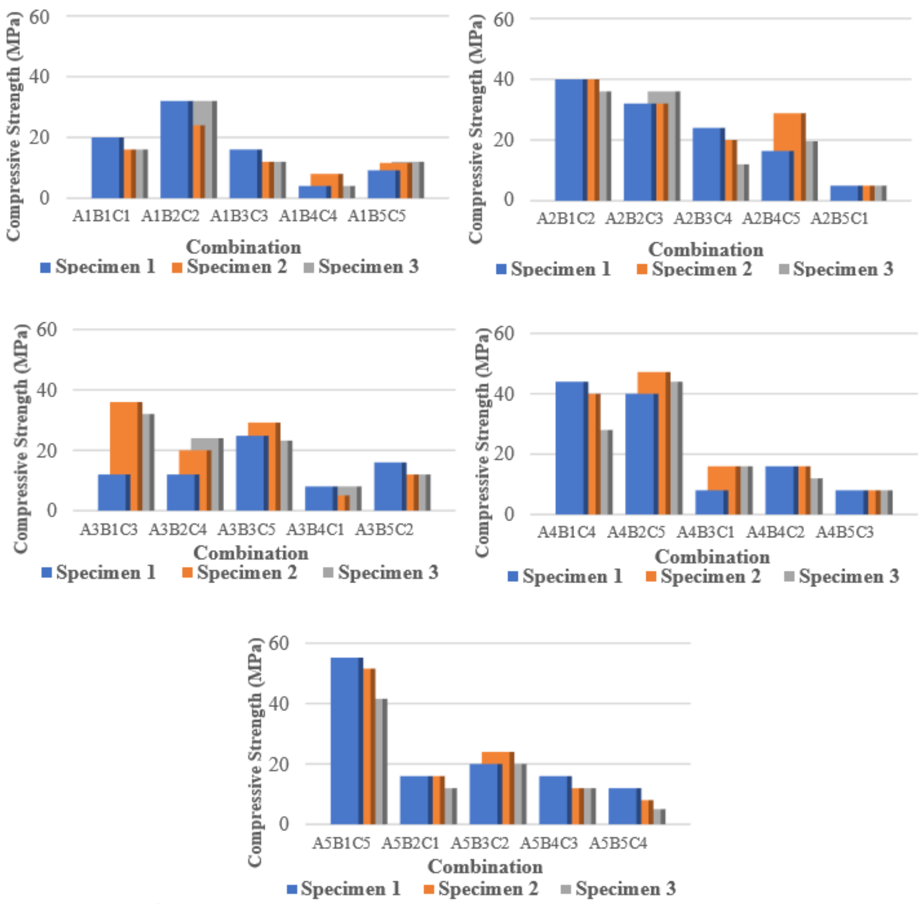

Figure (2): The average compressive-strength result based on molarity

This result occurred due to the molarity of the activator solution, as well as the catalyst solution and the percentage of accumulated water affecting the mechanical properties of the geopolymer mortar. The higher the molarity and the lower the percentage of water used in the geopolymer mixture, the higher the degree of liberation of the silica and alumina particles, thereby increasing the compressive strength of the geopolymer binder products (Hadi et al., 2017; Hardjito and Rangan, 2005; Mehta et al., 2017).

Precursor Ratio

The compressive-strength graph based on the precursor ratio of the eggshell powder and GGBFS is shown in Figure 3. The compressive strength of each specimen decreased with an increase in the factor-combination ratio from 60:40 to 100:0. The addition of GGBFS increased the compressive strength of the geopolymer mortar. The highest compressive strength of 55.2 MPa was achieved at a ratio of 60:40 for specimen 1, whereas the lowest compressive strength of 4 MPa was achieved at a ratio of 100:0 for B5 factors.

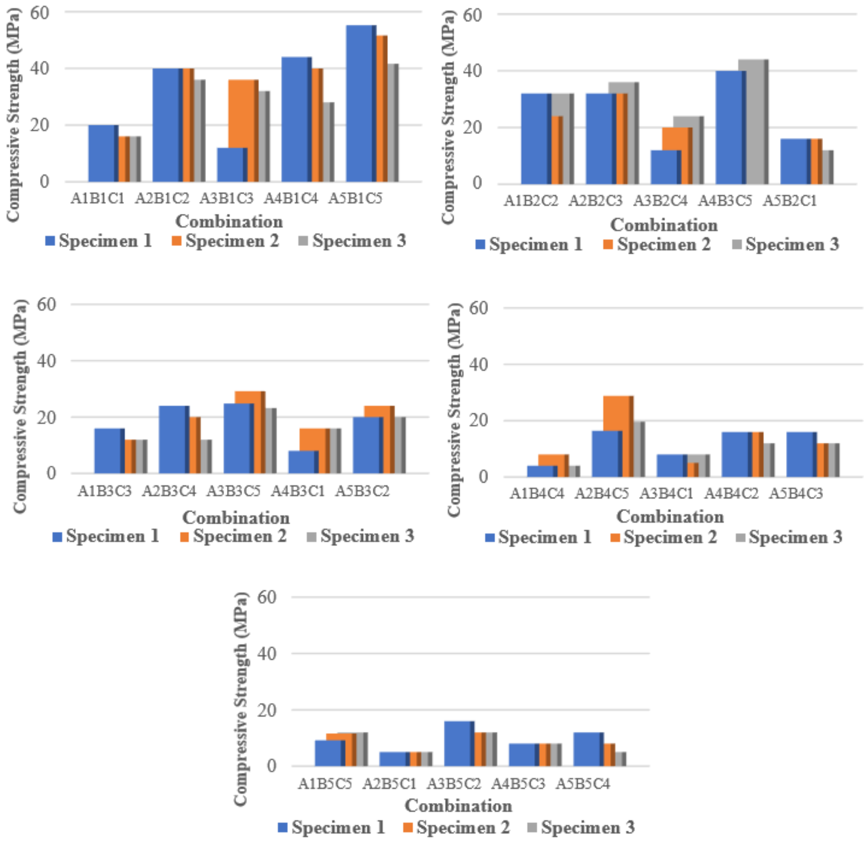

Figure (3): The average compressive-strength result based on the eggshell: GGBFS precursor ratio

This result occurred because of the relatively high GGBFS content in the precursor mixture, which enhanced the geopolymer bonding formation and afforded a high amount of calcium silicate hydrate (CSH) gel, thereby increasing the strength of the geopolymer concrete (Poorveekan et al., 2021). Meanwhile, the low amount of eggshell powder within the precursor mixture corresponded to a reduced amount of Al_2O_3, which restricted geopolymerization reactions and decreased the compressive strength (Bellum et al., 2020; Hadi et al., 2017). These findings can be deduced from the SEM and XRD characterization results.

Curing Duration

Figure 4 shows the compressive-strength results of various combinations based on curing duration. The analysis of the compressive-strength results based on curing duration shows a proportional increase in the compressive strength with the factors, from C1 to C5, as the curing duration increases from 3 days to 56 days. Geopolymers are a type of inorganic polymer formed by the reaction of an alumino-silicate powder with an alkaline solution. The lowest compressive strength observed, 4 MPa, was for a specimen cured for only 3 days. This suggests that the geopolymerization reactions were not yet complete, resulting in a less dense and weaker structure. On the other hand, the highest compressive strength, 55.2 MPa, was achieved with a curing duration of 56 days.

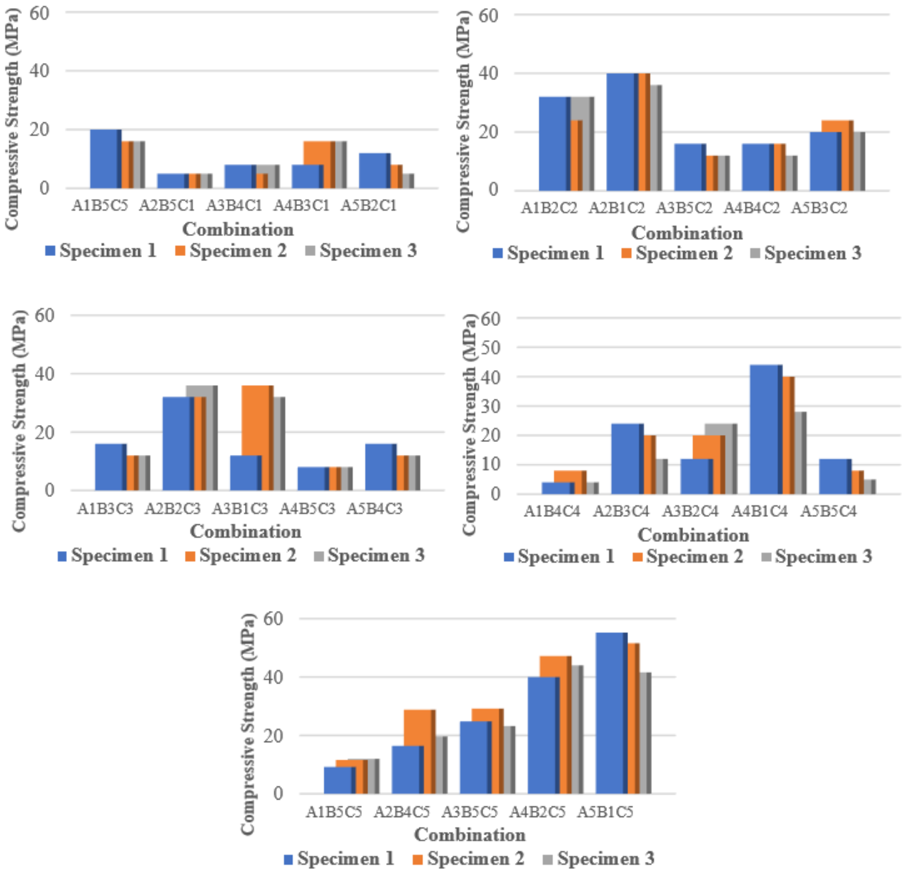

Figure (4): The average compressive-strength result based on curing duration

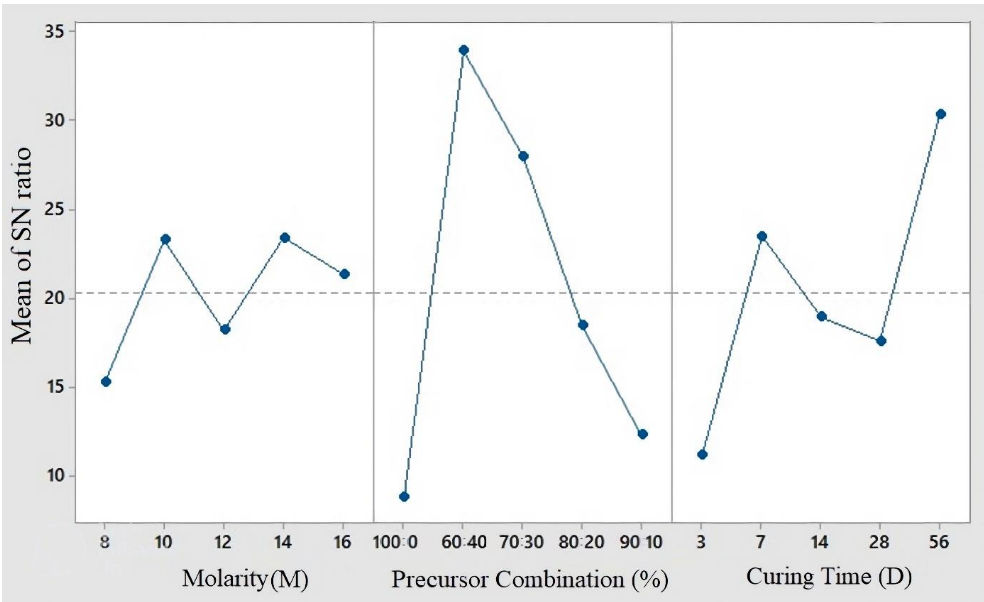

Figure (5): The signal-to-noise ratio graph for each factor in Taguchi design

The curing process, which involves maintaining the geopolymer at a specific temperature for a certain period, allows for the continuation of the chemical reactions that form the geopolymer structure. During the curing process, the alumino-silicate particles in the geopolymer react with the alkaline solution to form a three-dimensional network of aluminate and silicate structures. This network gives the geopolymer its strength. The longer the curing duration, the more complete these reactions can be, leading to a denser and stronger geopolymer structure. This indicates a well-developed and dense geopolymer structure, resulting in high strength affecting the compressive strength of the geopolymer (Poorveekan et al., 2021; Shekhawat et al., 2019).

Analysis of the Signal-to-Noise Ratio Based on the Taguchi-method Results

The SN-ratio analysis was conducted for the compressive-strength results based on the Taguchi method exhibited in Figure 5. The analysis was used to identify the control factors that reduce the variability in the Taguchi method by minimizing the effects of uncontrollable factors (noise factors). At high S/N ratios, control-factor settings that minimize the effects of the noise factors can be identified.

The S/N ratio obtained using the Minitab 18 software was employed to analyze the compressive strength of each factor in the Taguchi method. Based on the S/N-ratio curves, the highest delta of 11.59 was achieved by the precursor ratio, whereas the lowest of 3.20 was achieved by the molarity factor. The higher the S/N ratio, the higher the factor's effect, because the results of this research were obtained in relation to the compressive strength. Notably, the higher the compressive strength, the higher the quality of the geopolymer concrete produced. Therefore, this explains the influence order of the factors toward the compressive strength of the geopolymer mortars, i.e., precursor ratio, curing duration and molarity.

Consistency and Setting Time of the Blended Geopolymer

The consistency and setting time of the geopolymer concrete was assessed for A5B1C5 and A2B1C1 combinations, as listed in Table 6. The concept of consistency in the context of cementitious materials refers to the inherent property of a freshly-mixed cement paste, mortar or binder mix to exhibit flowability. The parameter commonly referred to as the consistency of cement is alternatively known as the standard consistency or normal consistency.The initial and final setting times of the geopolymer paste without the coarse and fine aggregates are reported in this paper. The initial setting period was calculated from the moment at which the mixing process began until the needle had pierced the base-plate mold at a spot 5 mm below the bottom (Hadi et al., 2017). The total setting time was calculated from the beginning of the mixing process until the point at which the needle left no trace on the previous surface.

Table 6. Consistency and setting-time results of the geopolymer mortar

Trial	Factor Combination	Consistency (%)	Setting Time (min)	
			Initial	Final
10	A2B5C1	29	240	540
21	A5B1C5	37	15	30

The initial and final setting times of A5B1C5 with an eggshell: GGBFS ratio of 60:40 are 15 minutes and 35 minutes, respectively, whereas those of A2B5C1 with a precursor ratio of 100:0 are 240 minutes and 540 minutes, respectively. It was discovered that the addition of GGBFS accelerated the polymerization of the geopolymer by reducing its setting time. The impact of GGBFS on the setting time is comparable to that of limestone, in which the hydration reaction with tri-calcium silicate (C_3S) provides a nucleation site in the hydration products of the geopolymer paste (Chong et al., 2020). Additionally, the effect of GGBFS addition on the A2B5C1 factor combination yielded a consistency result of 29%, whereas the A5B1C5 factor combination yielded a consistency result of 37%. This finding indicates that the addition of more GGBFS improves the relative mobility or flowability of freshly-mixed concrete, which includes the entire spectrum of fluidity from the driest to the wettest possible mixtures (Hadi et al., 2017).

SEM Analysis of the Precursor and Geopolymeric Binder

SEM-characterization results for the precursor; i.e., the eggshell powder and GGBFS, are depicted in Figures 6 (a) and (b), whereas the micrographs of the geopolymeric binder; i.e., A2B5C2 and A5B1C5 with eggshell: GGBFS ratios of 100:0 and 60:40, are displayed in Figures 6 (c) and (d). Figure 6 (a) shows that the eggshell particles are irregularly shaped, have a jagged morphology with homogenous sizes and exhibit a slightly porous surface because of the grinding treatment conducted. Meanwhile, Figure 6 (b) exhibits the irregular particle shape of the GGBFS, generally depicting larger particles than the eggshell particles. Therefore, this result was in agreement with thee particle-size distribution. Furthermore, the SEM micrograph shown in Figure 6 (c) indicates that the unreacted eggshells stick together, playing the role of a "micro-aggregate," forming unevenly distributed voids, which results in a porous microstructure and reduces the mechanical properties of the geopolymer (Shi et al., 2022). Compared with the geopolymer made of 100% eggshell (Figure 6 (c)), that with an eggshell: GGBFS ratio of 60:40 was more uniform and compact; further, it had the smoothest surface with dense and fewer voids in the geopolymer matrix, which indicates a high mechanical strength (Shekhawat et al., 2020a). Furthermore, the quantity of the produced CSH shown in Figure 6 (d) is higher than that of the CSH shown in Figure 6 (c). The geopolymeric gels, such as the CSH and CASH, are accountable for the improvement in the mechanical strength (Shekhawat et al., 2020b). Various studies regarding the identification of polymerization on the surface of the geopolymer mortar have been reported (Elchalakani et al., 2018; Qiu et al., 2019).

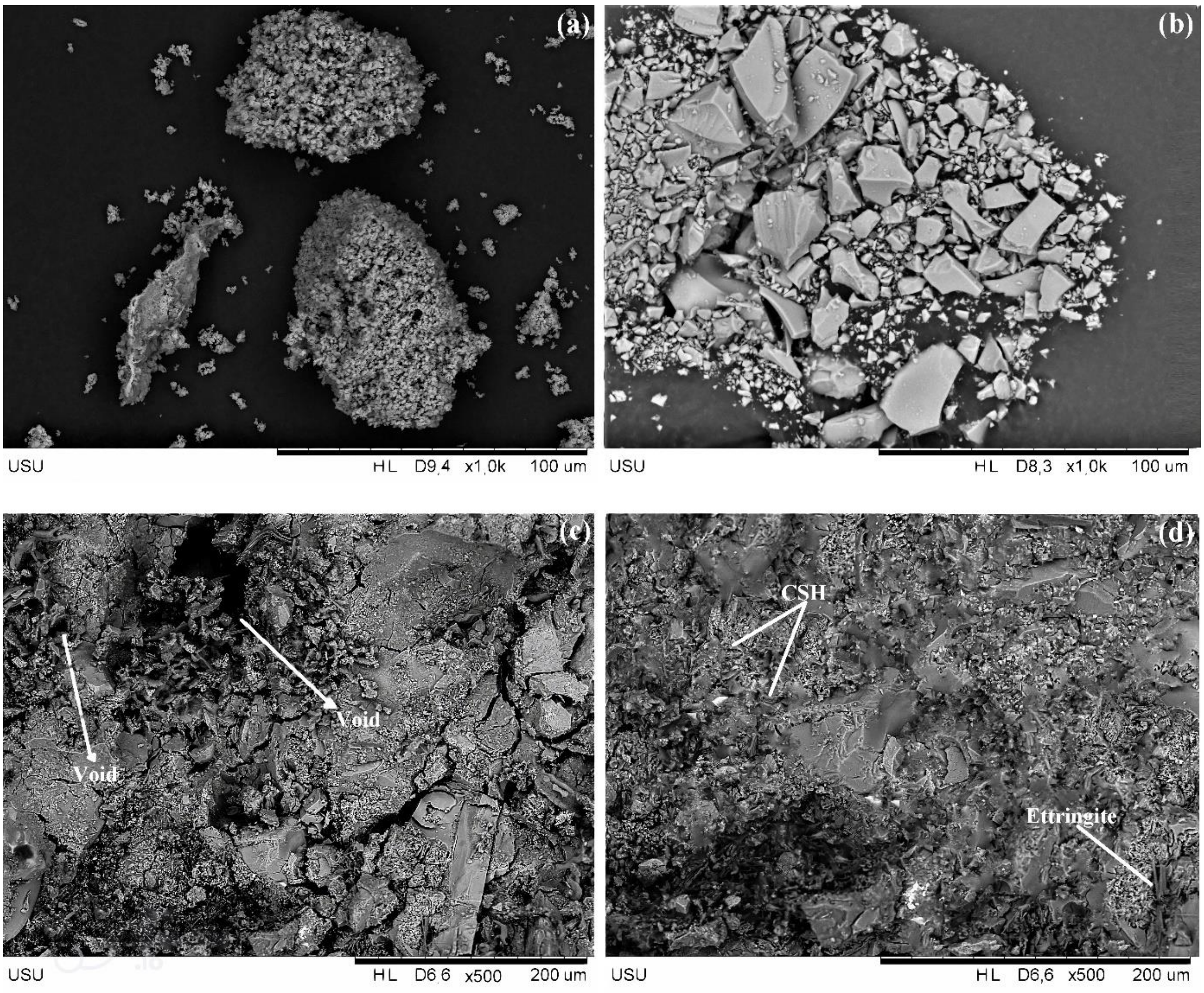

Figure (6): SEM results of the eggshell (a), GGBFS (b), A2B5C1 (c) and A5B1C5 (d)

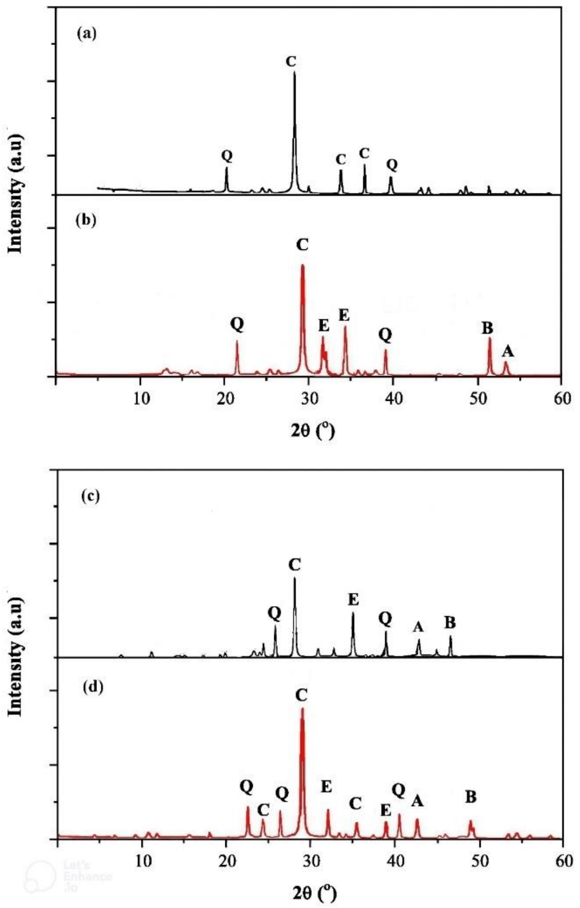

Figure (7): XRD results of the GGBFS (a), eggshell (b), A2B5C1 (c) and A5B1C5 (d)

XRD Analysis of the Precursor and Geopolymeric Binder

The raw materials, GGBFS, eggshell and geopolymeric binders, of A2B5C2 and A5B1C5, were subjected to XRD tests. Figure 7 (a) shows that GGBFS is mainly amorphous and contains calcium; i.e., calcite ($CaCO_3$) and quartz (SiO_2), indicating the potential of the geopolymerization process. Conversely, Figure 7 (b) shows that the eggshell is mainly composed of calcite ($CaCO_3$), quartz (SiO_2), eskolaite (Cr_2O_3), bornite (Cu_5FeS_4) and alumina (Al_2O_3). These results are consistent with the provided XRF data and several reported studies (Bellum et al., 2020; Brahimi et al., 2020a; Lemougna et al., 2020). Furthermore, Figure 7 (c) exhibits the XRD-characterization result for the geopolymer with the factor combination of A5B1C5, where the mineralogical phases were calcite ($CaCO_3$), quartz (SiO_2), eskolaite (Cr_2O_3), alumina (Al_2O_3) and bornite (Cu_5FeS_4). This result mainly highlights the mineralogical properties of eggshell, which do not significantly change. Meanwhile, the XRD-analysis result presented in Figure 7 (d) exhibits the major phases of quartz, calcite and albite. The other phases; i.e., eskolaite and bornite, are considered the typical phases of the added GGBFS. The formation of the polymerization product was associated with the presence of quartz, calcite and albite, whereas each phase was composed of SiO_2, $CaCO_3$ and $NaAlSi_3O$ (Mehta et al., 2020). The quartz and albite formations verified the polymerization product of sodium alumino-silicate hydrate (NASH), whereas calcite-quartz and albite-quartz formations corresponded to calcium-based CSH and CASH, respectively (Brahimi et al., 2020b; Dong et al., 2017; Yip et al., 2005). Each formation was proven by the XRD results, which were identified as key factors for imparting strength against the external loadings. Therefore, the mixtures of A5 molarity and B1 precursor ratio were the best combinations for the geopolymer mortar, which was proven by the crystalline-phase result.

CONCLUSIONS

This study investigated the synthesis of eggshell powder and GGBFS based on a geopolymer designed by the Taguchi method. The experimental study was undertaken to assess compressive strength through the Taguchi L25 method using 3 factors; i.e., molarity (A), precursor ratio (B) and curing duration (C). The SN-ratio, consistency and setting time, particle-size distribution, XRF, SEM and XRD analyses were conducted on the specimens. Based on the experimental outcomes, the following conclusions have been drawn:

- The particle-size distribution shows that the eggshell particles are finer than 10 µm, whereas the GGBFS particles are less than 1000 µm, which affects the surface area when geopolymerization takes place.
- The XRF result of the raw material showed that CaO, SO_3 and K_2O were the highest constituents of the eggshell; conversely, CaO, SiO_2 and Al_2O_3 were the highest constituents of GGBFS.
- The Taguchi-method results showed that the highest compressive strength was generated from the following optimized factors for the considered parameters: NaOH molarity of 16 M, precursor ratio of 60:40; i.e., eggshell: GGBFS and curing duration of 56 days. However, 10 M, 100:0 ratio and 3 days were the worst factor combinations, generating the

lowest compressive strength.

- The SN-ratio analysis results showed that the most influencing factor from the Taguchi method was the precursor ratio; i.e., eggshell: GGBFS; the compressive-strength result was affected by the different ratios.
- The highest consistency and shortest initial and final setting times were obtained for the optimum factor combination, whereas the poorest factor combination resulted in the lowest consistency and the longest initial and final setting times.
- The observations and interpretations of the SEM-and XRD-test results showed that the geopolymerization of eggshell: GGBFS at 60:40 was successful, because it was uniform and compact; further, the CSH gel was produced and it afforded the smoothest surface with a denser and lesser void than the specimen of the 100:0 precursor ratio.

Acknowledgements

This research is financially and technically supported by a university grant from Universitas Sumatera Utara [469/UN5.2.3.1/PPM/SPP-TALENTA USU/2021], Ministry of Education, Culture, Research and Technology, Indonesia.

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