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RESEARCH ARTICLE

Influence of Early Microwave Curing on Performance of Slag-Based Geopolymer Mortars

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ABSTRACT

In this article, an experimental study was conducted to examine the effect of curing time and microwave power on the compressive strength of early microwave-cured slag based geopolymers. Geopolymers have the potential to serve as an environmentally friendly substitute for cement-based building materials, and the use of microwave curing to geopolymers holds the promise of substantial strength improvement. Different microwave curing energies (300 - 800 Watts) were utilized at varying durations (10 - 60 minutes) on demoulded mortar specimens after one day. After that, compressive strength tests were conducted on both the cured and uncured specimens at three different ages: 1, 7, and 28 days. Results indicated that microwave curing could increase the strength about 10 times (36,47 MPa) in 1 day which is almost equal to the 28 days strength of uncured specimens. Based on the performed SEM-EDX results and visual inspections there may be a correlation among EDX results, color changes and compressive strength values. High energy level such as 800-Watt caused decay in samples and durability problems by decreasing the strength at late ages; Therefore, it is recommended to not apply such high energies to slag-based geopolymers.

Keywords: Geopolymer, Ground granulated blast furnace slag, Microwave curing, Strength, SEM-EDX analysis

1. Introduction

Due to the widespread usage of concrete in the construction industry today, cement is increasingly employed as a binder in concrete. More than 4 billion tons of cement are produced annually on a global scale, and the utilization of cement is seeing exponential growth [1]. An estimated 5–7 percent of all carbon dioxide released into the atmosphere is generated during the production of cement; hence, cement production is one of the primary contributors to the acceleration of global warming [2]. As a result, scientists concentrated on developing environmentally friendly substitutes for cement. In recent decades, there has been a growing scientific and engineering interest in a substance called geopolymer, which is often regarded as an environmentally beneficial material [3]

Mechanically, geopolymer is comparable to conventional Portland cement concrete, but it is more resistant to durability issues [3]. However, initiator materials utilized in the fabrication process have a significant impact on the characteristics of the geopolymers produced. Alkaline environments have a substantial impact on the geopolymerization process and, consequently, geopolymer properties. In an alkaline solution, the compressive strength values of geopolymers increase as the sodium silicate to sodium hydroxide ratio ($\text{Na}_2\text{SiO}_3/\text{NaOH}$) rises. Additional key aspects are the molarity (concentration) of sodium hydroxide and the ratios of Na_2O , H_2O , and SiO_2 in sodium silicate solution. Generally, a greater concentration of sodium hydroxide results in enhanced strength. And NaOH stimulates the development of CH gel, which is recognized for its ability to improve strength performance [4]. Curing conditions follow-up to the synthesis of geopolymers have

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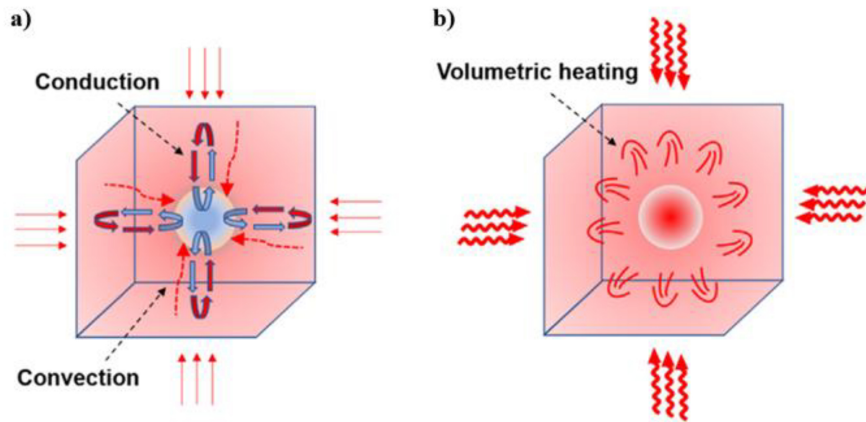


Fig. 1. Comparison of traditional and microwave curing; a) conventional and (b) microwave heating patterns.

a significant impact on their strength qualities, with the exception of the initiator materials utilized. Three common curing types examined in the literature are ambient curing [2, 5], heat/oven curing [6, 7], and steam curing [8]. It has been shown by Hardjito et al. (2005) and Vijai et al. (2010) that the mechanical strength of geopolymer concrete is enhanced at higher curing temperatures [4, 5]. It was determined that an optimal curing duration of one day at 60°C in an oven was optimal. The oven curing method has been shown to be the most suitable and effective approach for curing geopolymer concrete with regards to the development of early strength [5, 7, 9]. Through these investigations, it can be concluded that conventional heat or oven curing is the most effective curing method. Nevertheless, this curing method has significant disadvantages, including the fact that it is challenging to implement in situ. When heat is delivered to the surface and permitted to convectively reach the core, temperature gradients also develop throughout the specimen. By employing oven curing, the sample is shielded from uneven heating, which may result in the formation of undesired properties [10]. Recent studies have shown that strength can be significantly enhanced using microwave curing as a novel technique, even with a curing time of less than 60 minutes. In contrast, when strength levels were maintained for 24 hours using a traditional oven, comparable results were obtained [11, 12]. A comparison between heat curing and microwave curing is illustrated in Fig. 1.

Clearly, the sample's core was subjected to a higher temperature, and microwave curing more evenly distributes heat than conventional heat curing [13]. For instance, Lei et al. (2023) has applied microwave curing on basalt and waste glass-based powder mixtures. While surpassing 180 W may have negative effects, prolonging the microwave curing period can improve the compressive strength. The strength attained fol-

lowing 7 minutes of microwave curing is equivalent to that attained after 28 days at normal temperature [14]. Lei et al. (2024) has also focused on calcination ratio of basalt on microwave efficiency. They calcinated basalt tailing raw material between 500-1000 °C and applied optimized microwave curing regime they previously found (180W 7 minutes) revealing that calcination at 750°C resulted best compressive strength [15]. These studies show the efficiency of microwave curing on basalt tailing based geopolymers. However, even calcination heat of precursor influenced microwave curing efficiency.

Recent research on geopolymers has also demonstrated that microwave curing is an effective method for producing products with high early strength, including precast concrete and geopolymer foam [16, 17]. This efficiency guarantees that microwave irradiation for geopolymers will be very applicable. However, selecting the inappropriate curing energy level and duration may result in insufficient strength, and depending on the geopolymer, higher energy levels and longer duration may be detrimental. With regard to durability issues, these two parameters of microwave curing application should be taken into account with the initiator materials utilized in the manufacturing of geopolymers. Some studies discussed in the following section revealed that applicable microwave power and curing durations to achieve adequate strength and durability related with mix design and precursor type.

Microwave curing, in which the materials get microwave energy via chemical interactions with the electromagnetic field, is an alternative to heat curing [10, 18]. Subsequent to microwave irradiation, materials may manifest three discernible behaviours: insulating, reflecting, and dielectric. Materials used as insulators, such as quartz, ceramic, and Teflon, are microwave permeable. Metals and alloys that reflect microwaves or absorb them minimally may qualify as

reflecting materials. As a type of dielectric substance, geopolymer exhibits neither reflective nor offensive properties. The microwave absorption capability of dielectric materials is determined by the relative dielectric constant, denoted as ϵ' , where ϵ'' represents the loss factor. In dielectric materials, microwave energy was converted to heat energy via the dissipation factor (loss tangent ($\tan \delta$)). The loss factor is represented by Eq. (1), where ϵ_0 is the absolute permittivity of the vacuum [13].

$$\tan \delta = (\epsilon' / \epsilon_0) / (\epsilon'' / \epsilon_0) = \epsilon'' / \epsilon' \quad (1)$$

When microwave curing is utilized, two crucial parameters that have an impact on the geopolymers are the curing duration and power. In order to achieve the required quality of the end product with geopolymers, it is necessary to identify these elements. Several findings from the literature about the applications of microwave curing can be categorized as follows:

Samantashingar et al. (2020) employed a range of microwave irradiation powers, including 200, 300, and 600W, to treat fly slag-based geopolymer for intervals of 10 to 60 minutes. They discovered that 600W curing for 30 minutes yields the highest compressive strength, which is nearly identical to the compressive strength recorded on the specimen after 60 minutes of 300W curing. In contrast to the 300W microwave power, however, the 600W microwave energy caused microcracks in the specimens [19]. The researchers have established that materials with the greatest compressive strength are produced through curing for sixty minutes using 300W microwave power [19]. Further investigations have established that energy exposure over 300W to geopolymer specimens may result in adverse consequences for the chemical formations contained inside their structures [3, 20]. Specific investigations were conducted utilizing microwave exposure at intensities exceeding 700 W for a timeframe of merely 10 minutes [21, 22]. In order to examine the impacts of different curing methods, they once subjected specimens of slag-based geopolymer reactive powder concrete to a variety of curing techniques, including microwave irradiation. For the duration of 4 minutes, 750W of microwave energy was utilized for the purpose of curing. The researchers noted that the compressive strengths and elasticity moduli of the specimens were enhanced with the use of microwave curing in comparison to air and heat curing [21]. Other research that concentrated on respectable energy levels discovered that the use of 450W of microwave power significantly increased strength [12, 23]. Another parameter might be alkaline solution have an impact on strength. Mayhoub et al. (2021) stated that an alkaline solution was

produced by curing 12N NaOH and Na_2SiO_3 solutions in the microwave; the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio was 2.5, and the highest strength value was obtained [21]. Similarly, according to Zamanabadi et al. (2019) using the precise molarity of sodium hydroxide and the same ratio of sodium silicate to sodium hydroxide improves the strength and durability of slag-based geopolymers [24].

The purpose of this study is to examine how the strength and durability of slag-based geopolymer mortar specimens are affected by early microwave curing applied on at different durations and powers. Additionally, the relationship between strength values and curing parameters was examined by looking at the physical impacts of curing on specimens by visual observations and microstructural analysis.

2. Material and method

2.1. Material

The experimental study employed slag (GGBS) obtained from local markets, which adheres to the criteria outlined in the ASTM C989 standard [25]. Particles of finely crushed limestone measuring no more than 5 mm in diameter were used for the formulation of geopolymer mortar. The raw materials utilized were ground granulated blast furnace slag and limestone crushed aggregates, as seen in Fig. 2.

Sieve analysis and physical properties of aggregate is given in Table 1. This investigation utilized a mixture of NaOH and Na_2SiO_3 as an alkaline activator. In addition, tap water and a superplasticizer based on carboxylic ether were chosen to ensure adequate workability. Physical and chemical properties of materials are given in Table 2.

2.2. Geopolymer sample production

Based on the literature review $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio was selected as 2.5 where the concentration of NaOH is 12N. For preparation of 1 kg of 12N NaOH solution, 361 grams of water and 639 grams of NaOH pallets were used. After NaOH got cooled down Na_2SiO_3 was mixed with the ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ solution was equal to 2.5. Prepared solution mix was kept in laboratory condition for about 24 hours before casting. Polycarboxylic ether-based superplasticizer and extra tap water in minimum amount as possible was also added to the mixture to achieve proper workability. In a literature study [9], the workability of FA based geopolymer concrete could be enhanced by adding up to 4% (by mass of FA) super plasticizer as similar to our study. However we used this amount on GGBFS based geopolymer which requires more water to achieve adequate workability. During



Fig. 2. Raw materials used to produce geopolymer mortar; a) crushed limestone fine aggregate b) ground granulated blast furnace slag.

Table 1. Sieve analysis results and physical properties of course and fine aggregates.

Sieve Size (mm)	Sieve Analysis						Physical Properties		
	5	4	2	1	0.5	0.25	Fineness Modules	Specific Gravity	Absorption
Fine Aggregate	100	84.1	49.6	30.5	14.5	3.8	2.46	2.51	2.8

Table 2. Available physical-chemical properties of main materials used to prepare slag-based geopolymer mortars.

Material Properties	Slag (GGBS)	Sodium Silicate (Na_2SiO_3)	Superplasticizer
SiO ₂	36,41	25,42	-
CaO	34,12	-	-
Al ₂ O ₃	10,39	-	-
MgO	10,26	-	-
K ₂ O	0,97	-	-
Fe ₂ O ₃	0,69	-	-
Na ₂ O	0,35	12,89	-
H ₂ O	-	61,69	-
Alkaline Content	-	-	< 3,0
Chlore-Ion Content	-	-	< 0,1
Density	2,9 g/cm ³	1,442 g/cm ³	1-1,1 g/cm ³
Color	Off white	Colorless	Green

the process of mixing flow table test was applied on the fresh mix according to ASTM C1437 [26] and it was found as 14 cm. Mix design for preparation of 1 dm³ slag-based geopolymer mortar are given in Table 3.

The following steps were taken to make geopolymer mortars: dry ingredients were poured into a pan mixer and stirred for two minutes. The second step was to gradually include the pre-prepared alkaline activator solution throughout the course of the subsequent two minutes of mixing. Thirdly, additional tap water and superplasticizer were added to the mixer within one-minute. Finally, the entire mixture was stirred for a further three minutes to ensure homogeneity. Two layers of fresh geopolymer slurry were poured into 70x70x70 mm³ cubic moulds after mixing. Air voids were eliminated from each specimen by subjecting them to a 15 second compaction using a vibrator. The specimen is then completely enveloped in plastic to prevent evaporation until the day of the

testing. The procedure of making geopolymer in this investigation is depicted in Fig. 3.

2.3. Test methods

The experimental study utilized a household type turntable microwave oven having 330x211x324 mm³ oven cavity and 2450 MHz operation frequency. It has seven power levels where minimum power is 100W and maximum power is 800W. The specimens were subjected to different levels of microwave power (300, 450, and 800W, from lowest to highest) and durations of exposure (10, 15, 30, and 60 minutes). Microwave cures were applied on specimens after demoulding at first day where 12 specimens were exposed to same curing regime. Each time 4 specimens were simultaneously positioned on the turntable with equal interval inside the microwave oven to ensure uniform distribution on each specimen, and the corresponding treatment was administered subsequent

Table 3. Mix design for preparation of slag-based geopolymer mortars.

Material	Slag (GGBS)	Fine Aggregate	Sodium Silicate (Na ₂ SiO ₃)	Sodium Hydroxide (NaOH)	Superplasticizer	Extra Water
Quantity (g)	495	1485	280	112	20	10



Fig. 3. Main process of slag based geopolymer mortar production: a) flow table apparatus and materials, b) mixer, c) mixing process, d) flow table test, e) moulded geopolymer specimens.

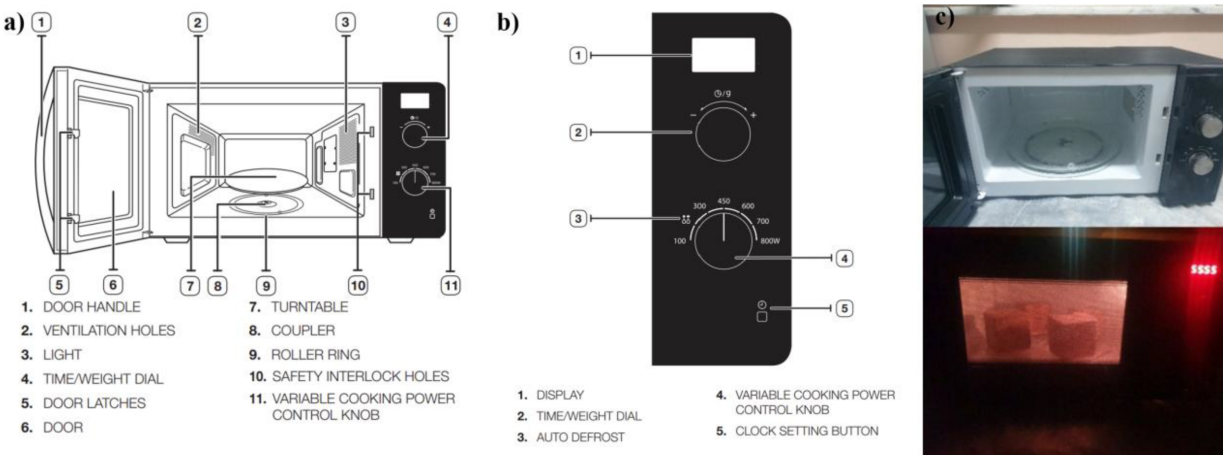


Fig. 4. Microwave curing process; a) used microwave oven [27] b) microwave oven control panel [27] c) microwave curing of mortars

to adjusting the energy level and duration on the microwave oven. The microwave treatment application and the utilized microwave oven are depicted in Fig. 4. After curing application specimens were weighted and 4 specimens underwent compressive strength testing in accordance with the ASTM C109 standard [28] subsequent to weighing. The strength tests were conducted to determine 1-day compressive strengths of both uncured (control) and microwave-cured specimens after cooling. Remained uncured and cured specimens were then sealed in plastic bags and stored in the laboratory until the 7th day and 28th day compressive strength tests were conducted. Just before the compressive strength tests density changes of all specimens were also measured. Images of cured and broken specimens were captured during the testing procedure to facilitate visual assessment. Subsequently, SEM and EDX analyses were conducted

at the 7-day and 28-day marks, respectively, to identify specimen degradation and chemical formation.

3. Results and discussion

3.1. Compressive strength

The average compressive strength results of control and microwave cured specimens at various ages are given in Fig. 5. In this figure “aWbM” was utilized to denote cured samples, with “a” representing the value of microwave power, “W” representing watt, “b” representing the curing time in minutes, and “M” signifying minute. For example, “800W10M” denotes the samples that underwent curing using 800 Watts of microwave energy for a duration of 10 minutes. “CONTROL” denotes the specimens that have not been treated.

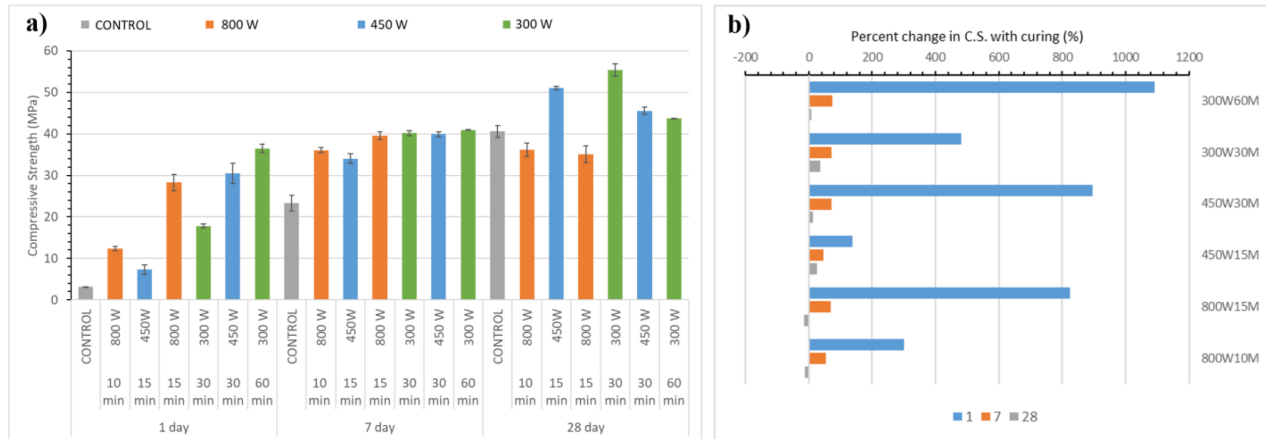


Fig. 5. a) Compressive strengths of microwave-cured specimens at various ages, b) percentage change in compressive strength with curing.

The results of compressive strength tests conducted on specimens for one day indicate that as the curing time increased, compressive strength values improved across all microwave energy levels. These results may provide evidence that microwave radiation has a strengthening influence on the compressive strengths of geopolymers. The disparity in strength values between cured and uncured specimens has significantly shrunk with the passage of time across all curing regimes. The observed outcome can be ascribed to the culmination of strength development in geopolymer mortars, as opposed to the detrimental consequence of microwave curing. All cured specimens retain their superior strengths to uncured specimens after seven days. However, the findings of a compressive strength test conducted after 28 days indicate that specimens were adversely affected by high-power microwave irradiation (800W), which resulted in a drop in strength when compared to uncured specimens of the same age. The strength reducing impact of increased energy or curing duration were also observed in the studies conducted by El-Feky and colleagues [22, 23]. In one study 720W microwave energy has caused durability problems when applied longer than 2 minutes while another study 450W microwave energy has caused durability problems when increased curing duration from 2 to 4 minutes. A significant study performed on fly ash based geopolymer has focused the effect of NaOH molarity in mix design has revealed that 240W energy is applicable up to 75 minutes when molarity of NaOH was 4 and resulted 9,53 MPa, while same energy is applicable up to 120 minutes when molarity of NaOH was 10 and resulted 56,87 MPa [18].

Microwave radiation speeded up heating at moderate energy inputs such as 300W in our study, increasing pozzolanic activation and promoting geopolymerization, which improves matrix densification and

mechanical strength. The method used with microwave assistance significantly reduces the time needed for materials to harden. In fact, a more effective distribution of significant ions promotes the creation of a less depolymerized gel and, as a result, a more stable structure [29].

On the other hand, rapid water loss, pore expansion, microcracking, and structural degradation might be brought on at early or later ages by excessive power such as 800W in our study or prolonged duration. Because different ingredients in the mixture have different dielectric characteristics, high energy input could create non-uniform temperature fields, which can lead to internal stresses and even thermal runaway[13, 30]. Based on these findings in addition to our experimental study not only curing regime but also mix design parameters material type and activator, the alkalinity of activator and even the Si/Al ratio inside the raw material highly effective on strength and durability [31]. Therefore, applicable curing energy and duration might be different for different geopolymers and mix design.

3.2. Visual observation

Fig. 6 presents visual examinations of control and microwave-cured specimens at various ages. Photographs were obtained immediately following curing on the first day following the casting of geopolymer mortar, and subsequently on days 1, 7, and 28 after conducting compressive strength tests, respectively.

The following conclusions can be drawn from the photographs obtained after curing:

- Surface humidity decreases with increasing curing time for all curing energies.

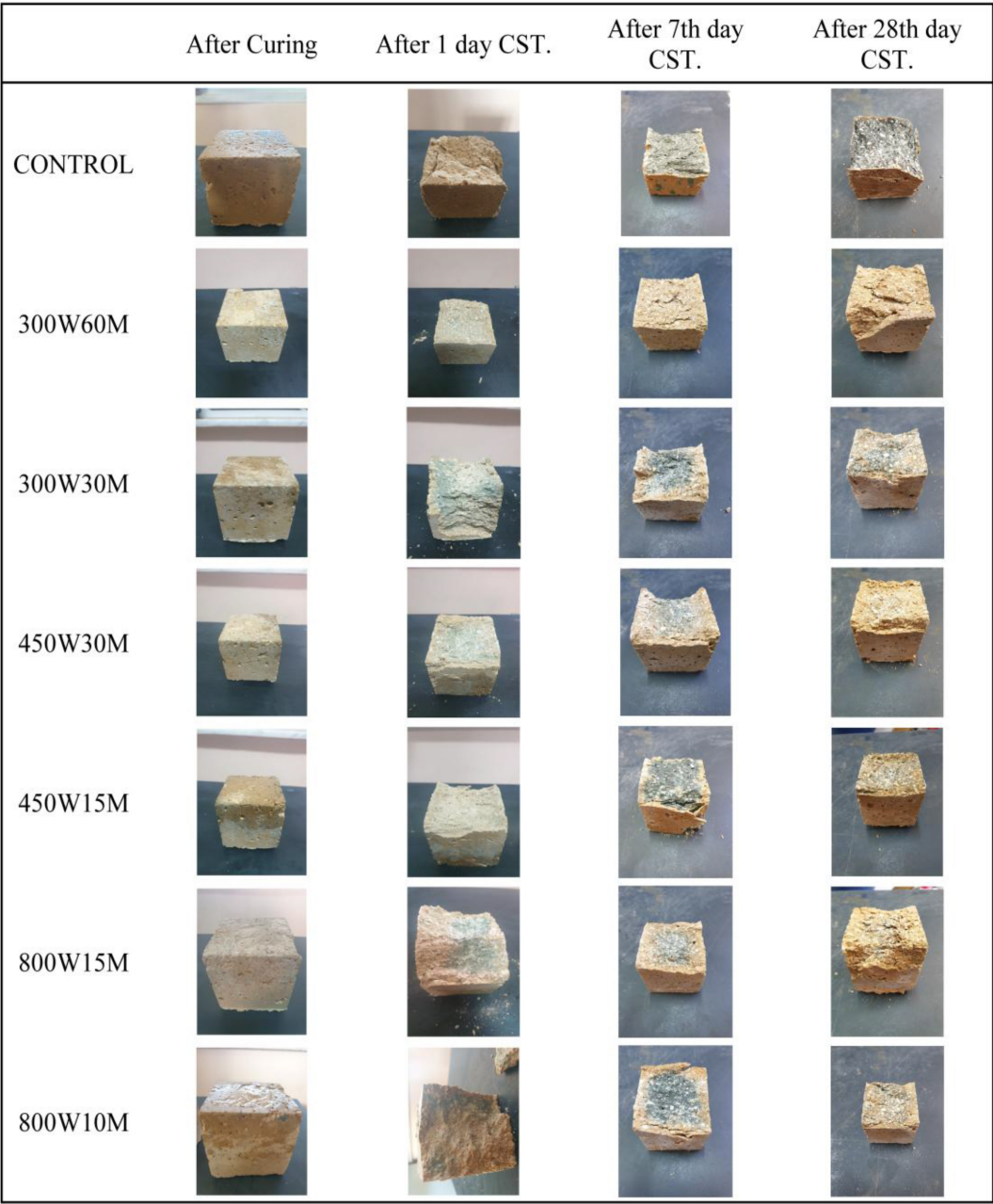


Fig. 6. Visual observations of geopolymer mortar specimens after microwave curing and after compressive strength tests applied at different ages.

- Crack formation might occur due to rapid moisture loss at high temperatures [32]. In the study performed by Yilmazer Polat B. (2019) 600W of microwave curing application caused noticeable cracks among other curing powers (200-300-400-500-600 Watts) [32]. However, cracks on the surfaces of the specimens caused by the curing conditions in our study are not notably distinguishable. For instance, much more cracks found on the surface of the specimen when exposed to 450 W microwave energy for 10 minutes compared to 15 minutes, although this difference is inconsequential when using 300W and 800W microwave energies. This phenomenon could be attributed to the effacement of surface fissures caused by prolonged microwave radiation, which may have originated from the rapid evaporation of water during early heating. This finding is consistent with the research conducted by Hong et al. (2019) [33]. Longer duration for same microwave

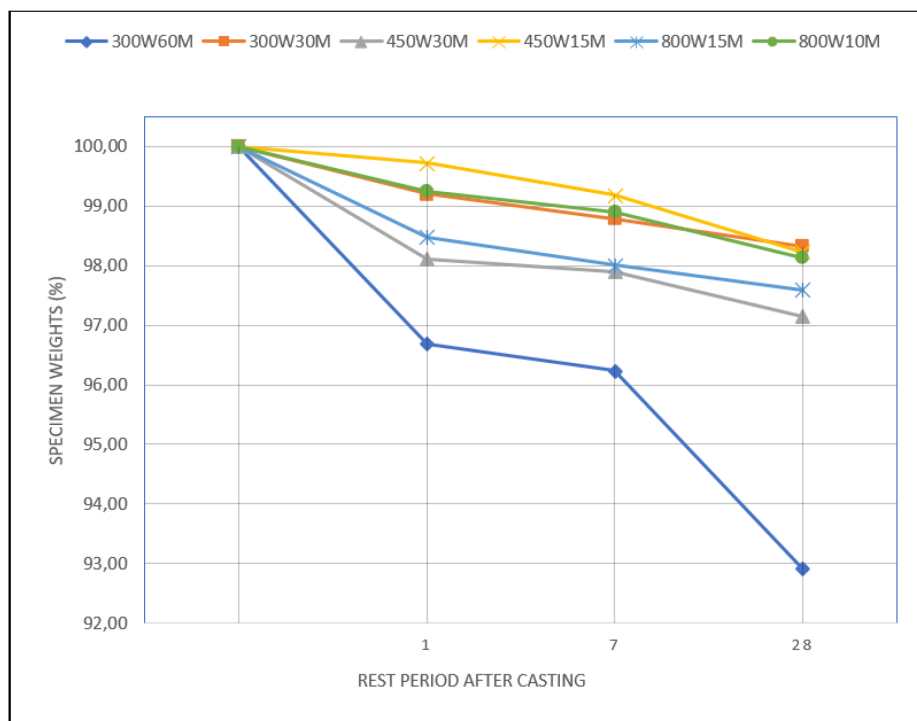


Fig. 7. Mass change of the specimens in percentage after microwave curing at different ages.

energy levels caused evaporation of the humidity on the surfaces of specimens due to higher surface temperature [34].

Additionally, photographs captured immediately following the compressive strength tests reveal that cured samples can be classified into two distinct categories based on the color of their cores: those that are lighter in color and those that are darker in color, which correspond to varying degrees of curing time. It is noteworthy that specimens subjected to microwave irradiation for shorter duration develop darker hues with time. Infer, particularly from 7-day images, that extended curing durations result in diminishing darkening at the centers. While no direct correlation between darkness and strength values has been established across all age groups, strength values are greater on days when the core is lighter. Conversely, strength values exhibit a decrease when the core reaches a weight of 28 days. Comparing 450W curing for 15- and 30-minute periods, for instance, the core color of 450W30M specimens was lighter than that of 450W15M specimens at both 7 and 28 days, despite the fact that compressive strength remained unchanged. 7 days after curing for 30 minutes, the compressive strength was greater, however it was decreased after 28 days. Interestingly, 300W60M specimens and 450W30M specimens had similar visuals for all ages consistent with their compressive strength.

3.3. Change in mass

Fig. 7 represents the change in density of mortars exposed to different microwave radiations. For the same energy levels more radiations caused more decrement in weights because of evaporation. All specimens were exposed to microwave curing only at 1-day ages after demoulding and slight decrements were observed for all specimens at first day.

300W60M curing caused significant decreasing on the weight of mortars and it can be easily distinguished from the other curing conditions. Since longer duration like 60 minutes of curing causes more evaporation in water at early stages. However, weight loss on these specimens have continued at different ages although there was no extra curing applied after 1 day. This can be attributed to a reason that longer curing at early stage might have caused evaporation of both free and chemically bonded water in the geopolymer structure and water content fell. When water content fell below a certain point chemically water tends to escape from geopolymer structure as reported in a study [33].

3.4. Microstructure analysis (SEM-EDX)

SEM and EDX analyses were conducted to examine chemical production and physical changes on the structure's surface. The SEM images of every

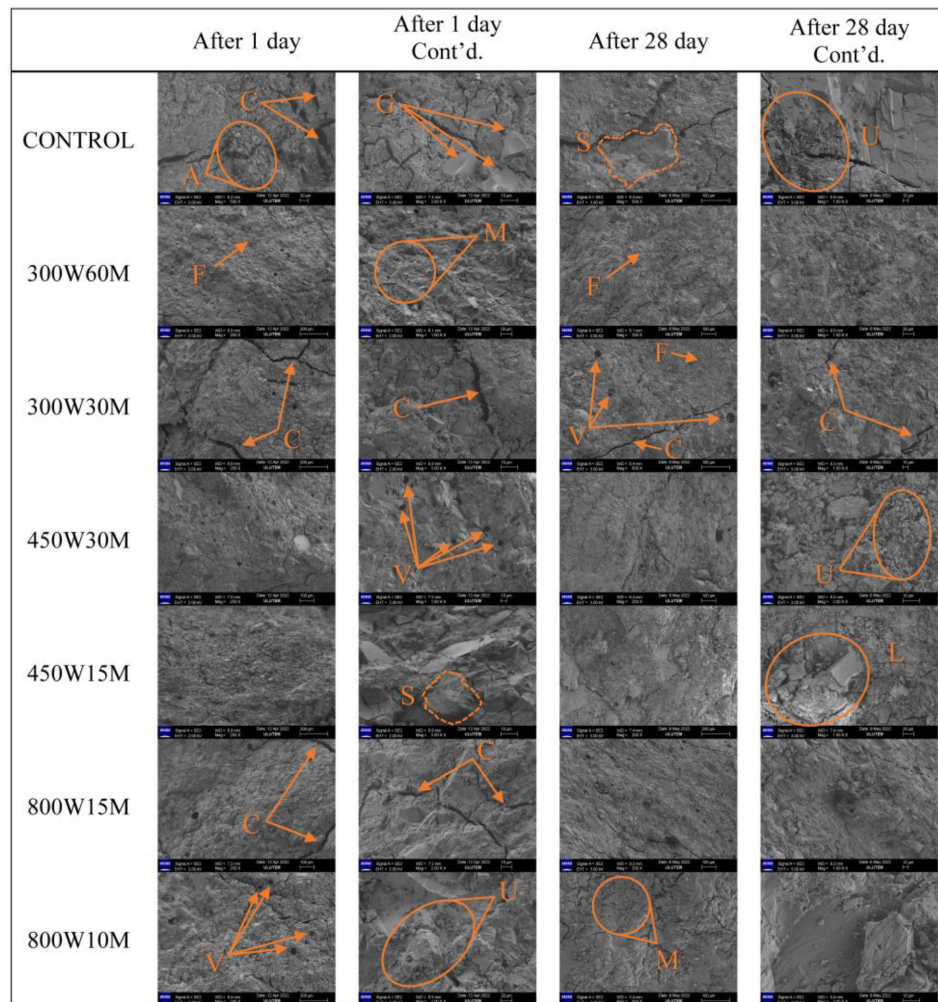


Fig. 8. FE-SEM images of microwave cured and control specimens after 1 day and 28 days (EHT = 2.00-3.00kV, Magnitude = 250X-3000X) A: agglomeration, C: cracks, F: firm structure, G: slag, M: microcracks, L: loose structure, S: sand, U: unreacted particles, V: voids.

specimen ranging from lower to higher microwave powers at 1 day and 28 days, are presented in Fig. 8.

The curing of slag-based geopolymers with microwaves has the subsequent effects on their microstructures, as determined by SEM analysis:

- At day 1, larger pores and fissures, as well as a denser agglomeration of unreacted particles, were seen in comparison to the control specimen after 28 days, due to the incomplete geopolymerization process. One day after curing specimens with 300W of microwave energy, the texture became significantly denser and more consistent, particularly after sixty minutes. This is due to the fact that the compressive strength level is the highest among all curing types. At day 1, specimens cured for thirty minutes under 450W microwave curing had less unreacted particles on the aggre-

gate surface than those cured for fifteen minutes. An identical outcome was obtained while employing 800W microwave curing. An extension in duration induces unreacted particles to participate in the polymerization process, which could account for the specimens' equivalent compressive strengths. Raw ingredients for geopolymers, including water, alkali activators, and slag, have diverse dielectric characteristics that are spread heterogeneously. Local thermal runaway is caused by the dielectric characteristics of these raw materials during microwave curing. This is the primary cause of sample deterioration [13]; it is attributed to its high internal strength.

- The control sample has a more pronounced porous structure in comparison to the microwave-cured samples, with the exception of 300W60M and 450W30M samples. As a result, specimens treated with microwaves had a more compact structure

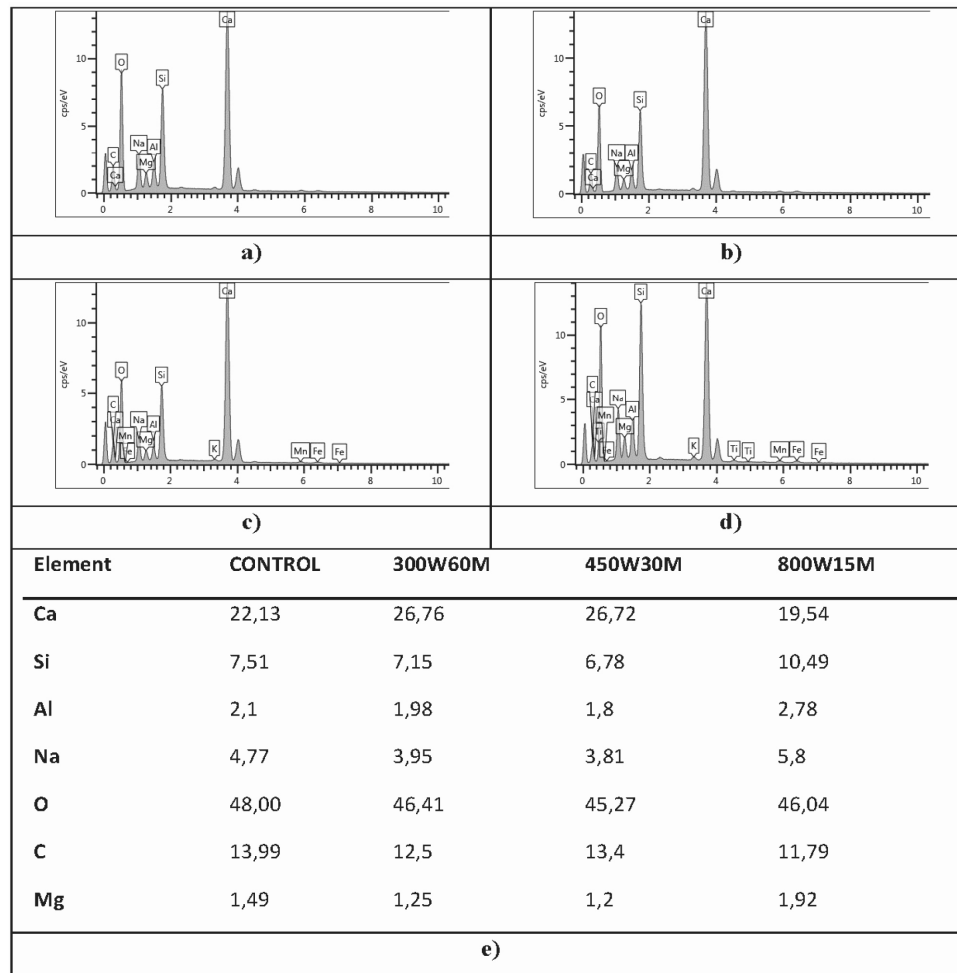


Fig. 9. EDX analysis results of the selected specimens after 28 days: a) CONTROL b) 300W60M, c) 450W30M, d) 800W15M, e) Weight percentage element distributions.

and a greater degree of slag. Geopolymerization potentially led to the formation of pores with reduced dimensions in the 300W60M and 450W30M samples; consequently, porous structures persisted and were visible on scanning electron micrographs of these samples [35]. The crack widths decreased as a result of microwave curing. This could be the result of gel forms filling the fissures [22]. However, prolonged exposure to microwave radiation can result in the formation of microscopic fissures in structures. As an illustration, microcracks were seen in 450W15M and 450W30M specimens after 30 minutes of curing on day one like in a previous study [13, 30].

Additionally, EDX analysis was conducted following the conclusion of compressive strength tests spanning 28 days. Due to the fact that microwave curing increases compressive strength in the early stages (one day), only those specimens with the highest compressive strength at that time were subjected

to EDX analysis. A control specimen was also included in order to compare the effects of curing and potential causes of microwave curing deterioration in the context of durability. The elemental content in the EDX analysis results could be useful to forecast the durability of samples subjected to different curing conditions and durations. Although EDX analysis was not commonly used in the literature studies regarding this topic, a previous study conducted EDX test on both oven cured and microwave cured geopolymers produced by various precursors [36]. The samples in that study were selected from the specimens having highest compressive strengths. They revealed contradictory EDX analysis results [36]. The percentage distribution of elements identified and the findings of the analysis done on the surfaces of the specimens in our study are displayed in Fig. 9.

Based on the following findings, EDX studies suggest that a correlation between element distribution and compressive strength may exist:

- The EDX values for 300W60M and 450W30M specimens are comparable to the compressive strength results, as illustrated in Fig. 9. Moreover, this relationship is virtually same for every element excluding oxygen (O). It is important to mention that the EDX results for the specimens were obtained following compressive strength testing for a period of 28 days. However, only those specimens with higher compressive strengths at day one were subjected to the EDX test. Consequently, the correlation between the compressive strength at 28 days and the EDX result at 28 days must be considered. The compressive strength of the specimens rose when the percentage of calcium (Ca) incorporated into the specimens was determined using EDX. Conversely, each of the remaining constituents suffered a decline.
- Since EDX analysis was conducted 28 days later, the geopolymer structure has become more compact in comparison to its early stages due to the geopolymerization process. Three processes comprise geopolymerization: dissolution, transport, and polycondensation [37, 38]. Early in the process, the Si/Al ratio cannot reach a high value due to the aluminum species' much faster participation in polycondensation to form Al-rich phase products and the greater susceptibility of Al-O bonds in the source materials to an alkaline assault than Si-O bonds. Later stages see the re-polymerization and dissolution of the Si-O species, which contributes to the increase in the Si/Al ratio. The Si/Al ratio for the cured specimens (300W60M, 450W30M, and 800W15M) is approximately 3.77, whereas it is 3.51% for the control specimen. This value is greater than that of the source material (1.825 Si/Al, calculated from Table 2), which is consistent with the findings of a prior study [33].

4. Conclusions

This study was conducted to measure the effect of early microwave curing on the strength of slag-based geopolymer mortars and to determine appropriate curing regimes. In addition to this, the study aims to investigate whether there is a relationship between strength results and visual inspection and petrographic analysis. Based on experimental results the following conclusions can be drawn:

- When comparing compressive strength values, it was observed that longer durations of microwave curing at an early stage resulted in greater strengths. For instance, specimens un-

cured (CONTROL) attained a strength of merely 3.06 MPa after one day, whereas the highest compressive strength value of 36.47 MPa was attained with 300 Watts of curing for 60 minutes. Although increased microwave energy, such as 800W, increased the compressive strength of these specimens within one day, their strength values decreased after 28 days, which is consistent with previous study. Moreover, across all age groups, the outcomes of 450W30M and 300W60M specimens in our experimental trial were identical.

- Visual studies conducted subsequent to mortar curing reveal that, with the exception of 300W60M specimens, the cores of all specimens get darker in some fashion. The even distribution of heat throughout the lengthier curing period is the cause of this. For all ages, no direct correlation between darkness and compressive strength values has been identified based on the color changes. However, 450W for 30 minutes and 300W for 60 minutes of microwave radiation induced comparable color changes in individuals of all ages. Therefore, the color distribution because of heat pattern throughout the specimen might give a hint about the compressive strength and durability performance even at early ages.
- Weight measurements of cured samples at various ages indicate that weight of the specimens reduced with longer curing as expected. However, weight of specimens cured by 300-Watt energy for 60 minutes continued to decrease until 28 days. This result was explained by the complex relation of water forms such as chemical bound waters tend to excess from structure when the total amount of physical and chemical bound water in the geopolymer is below a certain point.
- The results of scanning electron microscopy (SEM) indicated that microwave curing reduced the number of pores in all samples with the exception of 300W60M and 450W30M. The accelerated geopolymerization of slag particles could have potentially resulted in the formation of finer pore sizes. Additionally, water evaporation could have introduced additional voids into the structures of the 300W60M and 450W30M samples. Microwave irradiation may have also led to a reduction in crack widths, as gel formations likely filled the crevices, consistent with previous findings.
- The element distributions for 300W60M and 450W30M were nearly identical, which is consistent with the strength outcomes. According to the results of element distribution, strength values increased as the proportion of Ca content grew, whereas the percentage of other components

decreased, irrespective of the curing method. These data show that a direct relationship between compressive strength and element distribution may exist; thus, we recommend that future research do EDX analysis at younger ages rather than 28 days.

Consequently, early microwave irradiation is advised for slag-based geopolymers in order to get relatively high strength values in a shorter amount of time. The experimental investigation revealed that the results of SEM and EDX for compressive strength values, color changes, and aging of 300W60M and 450W30M specimens are comparable. Therefore, it is possible to apply either 300W for 60 minutes of curing or 450W for 30 minutes of curing. At later phases, however, elevated microwave energy such as 800W had adverse consequences, consistent with similar energy levels in literature study. Based on these results, in future studies petrographic analysis suggested to be performed at early ages. Furthermore, microwave power and curing duration can be selected based on color changes on specimen such as uniform color distribution or barely dark colors at core of the specimen at day 1 might be sign of very high early strength without causing durability problems at late ages.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article.

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Author's contributions

Contribution of each author who contributed the article is given below;

Author #1 Ahmet Taşdemir: Drafted and wrote the manuscript, performed the experiment and result analysis.

Author #2 Abdulkadir Çevik: Supervised the experiment's progress and helped in manuscript preparation.

Ethics

There are no ethical issues with the publication of this manuscript.

References

1. Agency, IE. (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5° C Goal in Reach.
2. Jindal, B. B. (2019). Investigations on the properties of geopolymer mortar and concrete with mineral admixtures: A review. *Constr Build Mater*, 227, 116644.
3. Tan, J., Cai, J., Huang, L., Yang, Q., Mao, M., Li, J. (2020). Feasibility of using microwave curing to enhance the compressive strength of mixed recycled aggregate powder based geopolymer. *Constr Build Mater*, 262, 120897.
4. Hardjito, D., Wallah, S. E., Sumajouw, D. M. J., Rangan, B. V. (2004). On the development of fly ash-based geopolymer concrete. *ACI Mater J*. <https://doi.org/10.14359/13485>
5. Vijai, K., Kumutha, R., Vishnuram, B. G. (2010). Effect of types of curing on strength of geopolymer concrete. *International Journal of Physical Sciences* 5.
6. Duxson, P., Fernández-Jiménez, A., Provis, J., Lukey, G., Palomo, A., Van Deventer, J. (2007). Geopolymer Technology: The Current State of the Art. *J Mater Sci*, 42, 2917–2933.
7. Nurrudin, M., Haruna, S., Mohammed, B., Shaaban, I. (2018). Methods of curing geopolymer concrete: A review. *International Journal of Advanced And Applied Sciences*, 5, 31–36.
8. Yewale, V. V., Shirsath, M. N., Hake, S. L. (2016). Evaluation of Efficient Type of Curing for Geopolymer Concrete. *International Journal of New Technologies in Science and Engineering*, 3.
9. Hardjito, D., Rangan, B. V. (2005). Development and properties of low-calcium fly ash-based geopolymer concrete.
10. Chowdhury, U., Neithalath, N., Mobasher, B., Rajan, S. (2013). Alkali Activated Systems Understanding the Influence of Curing Conditions and Activator Type/Chemistry on the Mechanical Strength and Chemical Structure of Fly Ash/Slag Systems.
11. Chindaprasirt, P., Rattanasak, U., Taebuanhuad, S. (2013). Role of microwave radiation in curing the fly ash geopolymer. *Advanced Powder Technology*, 24, 703–707.
12. Suwan, T., Paphawasit, B., Fan, M., Jitsangiam, P., Chindaprasirt, P. (2021). Effect of microwave-assisted curing process on strength development and curing duration of cellular lightweight geopolymer mortar, 36 1040–1048. <https://doi.org/10.1080/1042691420211885702>
13. Sun, Y., Zhang, P., Hu, J., Liu, B., Yang, J., Liang, S., Xiao, K., Hou, H. (2021). A review on microwave irradiation to the properties of geopolymers: Mechanisms and challenges. *Constr Build Mater*, 294, 123491.
14. Lei, S., Gao, H., Dai, H., Bernardo, E., Zhang, H., Yang, Q., Zhang, X., Wang, L. (2023). Characteristics of lightweight geopolymers from microwave curing of basalt and waste glass powder mixtures. *Constr Build Mater*, 409 133758.
15. Lei, S., Gao, H., Feng, R. et al. (2024). Effect of calcination temperature on the activity of basalt tailings for the lightweight

- geopolymer from microwave curing. *Mater Chem Phys*, 328, 129991.
16. Kastiukas, G., Ruan, S., Liang, S., Zhou, X. (2020). Development of precast geopolymer concrete via oven and microwave radiation curing with an environmental assessment. *J Clean Prod*. <https://doi.org/10.1016/J.JCLEPRO.2020.120290>.
 17. Nadeem, M., Ul Haq, E., Ahmed, F., Asif Rafiq, M., Hameed Awan, G., Zain-ul-Abdein, M. (2020). Effect of microwave curing on the construction properties of natural soil based geopolymer foam. *Constr Build Mater*, 230, 117074.
 18. Somaratna, J., Ravikumar, D., Neithalath, N. (2010). Response of alkali activated fly ash mortars to microwave curing. *Cem Concr Res*. <https://doi.org/10.1016/j.cemconres.2010.08.010>.
 19. Samantasinghar, S., Singh, S. (2020). Effects of curing environment on strength and microstructure of alkali-activated fly ash-slag binder. *Constr Build Mater*, 235, 117481.
 20. Graytee, A., Sanjayan, J. G., Nazari, A. (2018). Development of a high strength fly ash-based geopolymer in short time by using microwave curing. *Ceram Int*, 44, 8216–8222.
 21. Mayhoub OA, Nasr ESAR, Ali Y, Kohail M (2021) Properties of slag based geopolymer reactive powder concrete. *Ain Shams Engineering Journal* 12:99–105
 22. El-Feky, M. S., Kohail, M., El-Tair, A. M., Serag, M. I. (2020). Effect of microwave curing as compared with conventional regimes on the performance of alkali activated slag pastes. *Constr Build Mater*, 233, 117268.
 23. Mohsen, A., El-Feky, M. S., El-Tair, A. M., Kohail, M. (2021). Effect of delayed microwaving on the strength progress of Green alkali activated cement composites. *Journal of Building Engineering*, 43, 103135.
 24. Narimani Zamanabadi, S., Zareei, S. A., Shoaie, P., Ameri, F. (2019) Ambient-cured alkali-activated slag paste incorporating micro-silica as repair material: Effects of alkali activator solution on physical and mechanical properties. *Constr Build Mater*, 229, 116911.
 25. ASTM International. (2014). ASTM C989/C989M-14 Standard Specification for Slag Cement for Use in Concrete and Mortars. Annual Book of ASTM Standards Volume 04.02.
 26. American Society for Testing and Materials. (2020). ASTM C1437: Standard Test Method for Flow of Hydraulic Cement Mortar. ASTM International.
 27. Samsung Support Africa_En, MS23F301EAK [Internet]. Samsung; 2015 Oct [cited 2025 Sep 15]. Available from: https://www.samsung.com/africa_en/support/model/MS23F301EAK/SG/.
 28. ASTM International. (2020). ASTM C109 /C109M - 20b. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens). Annual Book of ASTM Standards 04.
 29. Tameni, G., Bernardo, E. (2025). Alkali Activation of Glass for Sustainable Upcycling: An Overview. *Ceramics* 2025, 8, 108 8:108.
 30. Dong, Y., El-Naggar, M. R., Gao, R., Li, Y., Zhao, Y. (2024). Impact of Microwave Pre-Curing on Pore Structure and Environmental Performance of Metakaolin- and Fly Ash-Based Geopolymers. *Buildings* 2024, 14, 3918 14:3918.
 31. Aschoff, J., Partschefeld, S., Schneider, J., Osburg, A. (2024). Effect of Microwaves on the Rapid Curing of Metakaolin- and Aluminum Orthophosphate-Based Geopolymers. *Materials* 2024, 17, 463 17:463.
 32. Yilmazer Polat, B. (2023). The influence of microwave curing on the strength of silica fume-added fly ash-based geopolymer mortars. *Journal of Sustainable Construction Materials and Technologies*, 8, 207–215.
 33. Hong, S., Kim, H. (2019). Effects of Microwave Energy on Fast Compressive Strength Development of Coal Bottom Ash-Based Geopolymers. *Sci Rep*. <https://doi.org/10.1038/S41598-019-52160-2>.
 34. Durak, U., Khaleel, F., Atiş, C., İlkentapar, S., Karahan O. (2021). The Effect of Microwave Curing on the Strength Development of Class-F Fly Ash-Based Geopolymer Mortar. *Erciyes Üniversitesi Fen Bilimleri Enstitüsü Fen Bilimleri Dergisi*, 37(1) 118–29.
 35. Aydin, S., Baradan, B. (2012). Mechanical and microstructural properties of heat cured alkali-activated slag mortars. *Mater Des*, 35, 374–383.
 36. Gultekin, A., Ramyar, K. (2022). Effect of curing type on microstructure and compressive strength of geopolymer mortars. *Ceram Int*, 48, 16156–16172.
 37. Davidovits, J. (1999). Chemistry of geopolymeric systems, terminology. *Second International Conference on Geopolymer*.
 38. Srinivasula Reddy, M., Dinakar, P., Rao, B. (2018). Mix Design Development of Fly Ash and Ground Granulated Blast Furnace Slag based Geopolymer Concrete. *Journal of Building Engineering*. <https://doi.org/10.1016/j.jobee.2018.09.010>.