Investigation of the Compressive Strength of Fly Ash–based Geopolymer Concrete cured by Oven and Microwave Radiation

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ABSTRACT

This study investigates the influence of three different curing methods -oven, microwave, and hybrid microwave–oven- on the compressive strength of Fly Ash (FA)-based geopolymer concrete. Five mixtures with an Alkaline Liquid (AL) to FA ratio varying from 0.6 to 1.0, combined with different curing conditions, were tested to evaluate the highest compressive strength values. The results revealed that the maximum compressive strength was observed at 30.2 MPa for oven-curing at 80 °C for 16 hours, 13.7 MPa for microwave curing at 400 W for 10 min, and 33.1 MPa for hybrid curing (microwave at 400 W for 10 min) followed by oven at 80 °C for 8 hours. These findings indicate that the hybrid curing method is an optimal solution, developing higher compressive strength in a shorter time compared to traditional curing methods.

Keywords-geopolymer concrete; fly ash; oven; microwave; compressive strength

I. INTRODUCTION

A more sustainable and eco-friendly solution to traditional Portland cement is geopolymer concrete [1]. This type of concrete utilizes industrial byproducts including FA, slag, or silica fume – materials rich in aluminosilicate minerals- as primary binders [2]. When these byproducts react with alkaline mixtures, they form a polymeric system that connects all the aggregates together, developing a stable and strong concrete mixture, with higher resistance to chemicals [3] and extreme conditions [4, 5], along with greater compressive strength [6, 7]. All these benefits make it essential for applications under extreme conditions, such as chemical plants, wastewater treatment facilities, and areas with high temperatures or aggressive chemicals. Additionally, its durability is related to longer lifespan, resulting in lower maintenance costs. While conventional Portland cement production generates high CO_2 emissions, geopolymer concrete reduces these emissions by up to 80% [1, 8]. Combined with its lower energy needs during production [7, 9], geopolymer cement is considered a promising solution in construction industry with a low environmental footprint. However, geopolymer concrete exhibits some limitations, including the availability of its raw materials, the need for advanced equipment, and the limited standardized guidelines.

FA geopolymer requires rather long heat curing to obtain reasonable strength development at an early age [10]. However, this long-curing period limits the application of this material. Therefore, alternative high-strength development methods with lower energy requirements have been considered. Microwave radiation represents an innovative evolution in the field of construction materials, utilizing microwave technology to improve the characteristics of geopolymer concrete. This process involves the material's exposure to microwave energy, generating heat internally within the concrete matrix. As a result, rapid and uniform curing is developed, further leading to faster strength development and improved material properties. Authors in [11] stated that the strength of FA-based geopolymer mortar treated with microwave radiation for under 12 min is equivalent to that of mortar thermally cured at 75 ◦C for 48 h. Similarly, authors in [12] demonstrated that microwave curing may reduce the preparation time of precast FA or Ground Granulated Blast-Furnace Slag (GGBS)-based geopolymer concrete in comparison to oven curing. Exploring the impact size of microwave-cured geopolymer paste, authors in [13] found that a 25 mm size geopolymer paste could reach a compressive strength of 56 MPa after being cured in a microwave oven for 5 min. In [10], an energy-efficient curing technique was proposed including 90 W microwave radiation for 5 min and heat curing at 65 ^{o}C for 6 h to manufacture geopolymer mortar. The results indicated that concrete's strength was equivalent to that cured at 65 °C for 24 h. It is evident that microwave curing effectively enhances the early strength of geopolymer composites. However, there is limited research focused on the combination between microwave and oven as a hybrid curing method for FA-based geopolymer concrete.

For this reason, this research examines the effect of three curing methods: oven (at 80 ^{o}C for 4, 8, 12, and 16 h), microwave (at three levels of power 100W, 200W, and 400W; for 3, 5, and 10 min) and hybrid microwave – oven, with AL to FA ratio varied from 0.6 to 1.0.

II. EXPERIMENTAL PROGRAM

A. Material and Mixture Proportions

An experimental program was designed to investigate the compressive strength of FA-based geopolymer concrete under three different curing methods: oven, microwave, and hybrid oven-microwave. The binder employed in this study was a combination of FA and ALs. FA type F was used with a density of 2500 kg/m^3. The chemical composition of FA is presented in Table I. ALs were blended with sodium silicates (Na_2SiO_3) and sodium hydroxide (NaOH) solutions. The components of the Na_2SiO_3 were Na_2O (9.4%) and SiO_2 (30.1%), with a modulus of 3.2. The selected concentration of NaOH solution was 10 M. The ratio of sodium silicate to sodium hydroxide solutions was chosen as 1:1, and the ratios of AL to FA by mass ranged from 0.6 to 1. Local sand with a density of 2610 kg/m^3 and crushed rock with a maximum size of 20 mm and density of 2720 kg/m^3 were used as fine aggregate and coarse aggregate, respectively. Details of the mixture proportions are provided in Table II.

TABLE I. FA CHEMICAL COMPOSITION

Oxide component	(%) by Mass
SiO_2	53.5
Al_2O_3	34.8
Fe_2O_3	4.1
CaO	1.2
K_2O & Na_2O	0.3
MgO	0.83
SO_3	0.25
Loss on Ignition (LOI)	8.87

TABLE II. MIXTURE PROPORTIONS OF EXPERIMENTAL WORK

Name	Coarse aggregate (kg)	Fine aggregate (kg)	FA (kg)	AL (kg)	AL/FA
GM1	1130	840	300	180	0.6
GM2	1130	810	300	210	0.7
GM3	1130	780	300	240	0.8
GM4	1130	750	300	270	0.9
GM5	1130	720	300	300	1

B. Sample Preparation and Test Method

FA-based geopolymer concrete consists of coarse aggregate, fine aggregate, FA, and alkaline solutions. Dry materials including FA and aggregates were mixed approximately 3 min after measuring. Then, the alkaline solution was poured into the solids, and the mixture was well stirred for about 4 min. The specimens with a diameter of 100 mm and a height of 200 mm were carefully cured after casting. The curing program contained three categories: oven, microwave, and hybrid oven-microwave. In the case of curing in an oven, the specimens were cured at 80 ^{o}C for 4, 8, 12, and 16 hours. In microwave curing, the specimens were dried at three levels of power -100 W, 200 W and 400 W- for 3, 5 and 10 min. The hybrid curing included the following steps: firstly, cured in microwave and then in an oven at 80 °C for 4 and 8 hours. The specimens were tested for compressive strength at a 28-day period following the ASTM C39/C39M standard [14], with a loading rate of up to 0.35 MPa/s. At least three specimens were used for testing to determine the mean compressive strength value. The details of the curing methods and experimental process are displayed in Figures 1 and 2.

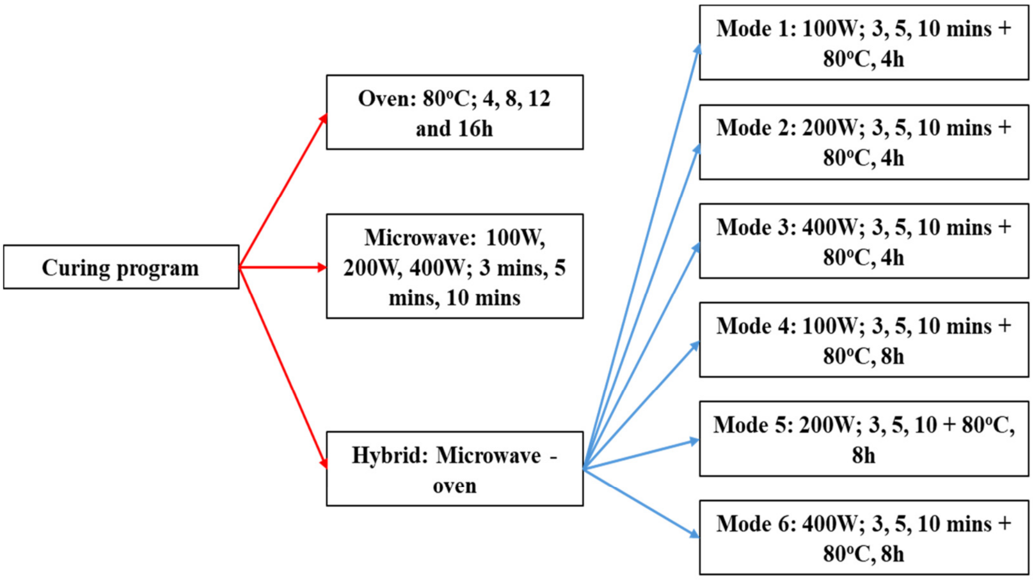


Fig. 1. Curing program of this study.

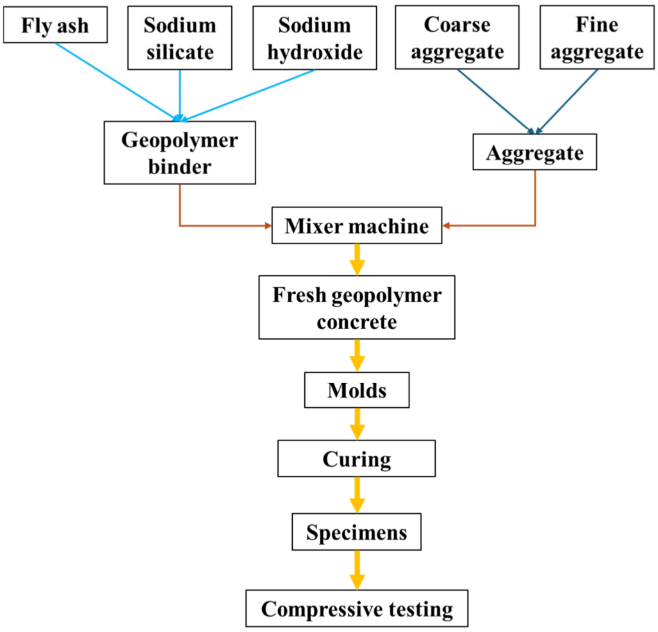


Fig. 2. Experimental process of this study.

III. RESULTS AND DISCUSSION

The experimental results examine the effect of curing conditions including curing in the oven at 80 °C for 4, 8, 12, and 16 hours and curing in the microwave at power levels of 100 W, 200 W, and 400 W for 3, 5, and 10 min. Testing specimens were produced using geopolymer concrete as GM1, GM2, GM3, GM4, and GM5/ The GM1, GM2, GM3, GM4, and GM5 test specimens were produced using geopolymer concrete.

A. Infuence of Alkaline Liquid/Fly Ash Ratio on the Compressive Strength of Geopolymer Concrete Cured in Oven

Figure 3 illustrates the influence of AL/FA ratio and curing time on compressive strength of FA-based geopolymer concrete after curing in an oven at 80 °C for 4, 8, 12, and 16 hours.

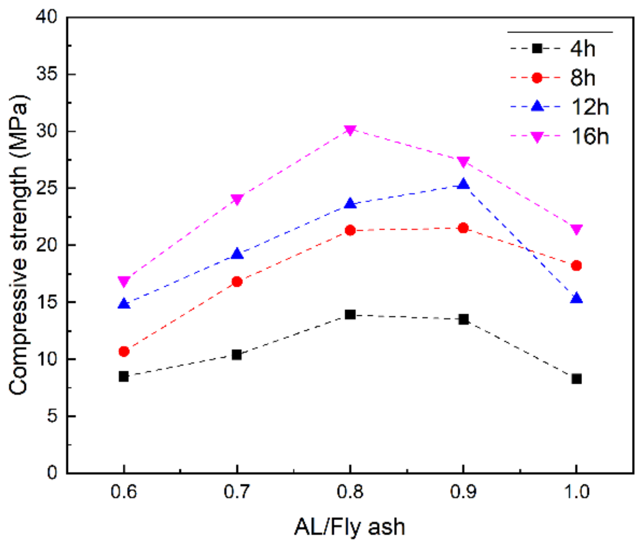


Fig. 3. Relationship between AL/FA ratio and compressive strength of geopolymer concrete cured in the oven.

When the AL/FA ratio increased from 0.6 to 0.8, the compressive strength of all specimens improved by 63.5%, 99.1%, 59.5%, and 78.7% for the curing durations of 4, 8, 12, and 16 hours, respectively. During the 16-hour curing period, the GM3 mixture reached the highest compressive strength value of 30.2 MPa. Similarly, when the AL/FA ratio was further increased from 0.8 to 0.9, two trends appeared. In the case of oven-curing for 4 and 16 hours, the compressive strength decreased by 2.9% and 9.3%, respectively, while in the case of oven-curing for 8 and 12 hours, the strength continued to increase by 0.9% and 7.2%, respectively. Finally, when the ratio changed from 0.9 to 1.0, the compressive strength of all specimens declined by 15.3% to 39.5%. This finding is consistent with previous research [15], which also observed a reduction in the compressive strength of geopolymer concrete as the AL/FA ratio increased from 0.9 to 1.0.

B. Influence of Alkaline Liquid/Fly Ash Ratio on Compressive Strength of Geopolymer Concrete Cured in Microwave

All mixtures were cured in microwave under three power levels for 3, 5, and 10 min, to assess the impact of AL/FA ratio on the material's compressive strength. Figures 4-6 depict this relationship at 100 W, 200 W, and 400 W, respectively.

In Figure 4, it is observed that as the AL/FA ratio increased from 0.6 to 0.8, the compressive strength of geopolymer concrete gradually raised. However, when the ratio changed from 0.8 to 0.9, the compressive strength of the mixtures cured for 3 and 5 min showed a slight increase, while at 10 min, it declined. At a ratio of 1.0, the compressive strength of all specimens decreased by 21% to 27.7%. Notably, the highest compressive strength was 8.4 MPa at 0.8 ratio,with 10-min curing.

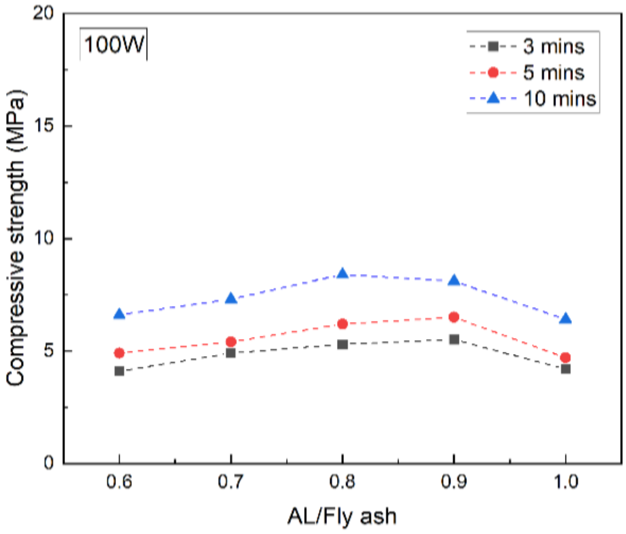


Fig. 4. Relationship between AL/FA and compressive strength of geopolymer concrete cured in the microwave at power level of 100 W.

In Figure 5, as the AL/FA ratio increased from 0.6 to 0.8, the compressive strength of specimens also raised. This trend continued for the 3-min curing period when the ratio was further increased from 0.8 to 0.9. However, for speciemens cured for 5 and 10 min, the compressive strength decreased by 23.4% and 7.8%, respectively. At a ratio of 1.0, the strength of geopolymer concrete declined from 4.2% to 21.1%. At the power level of 200 W, the highest observed compressive strength was 11.5 MPa, achieved at a 0.8 ratio with 10-min curing.

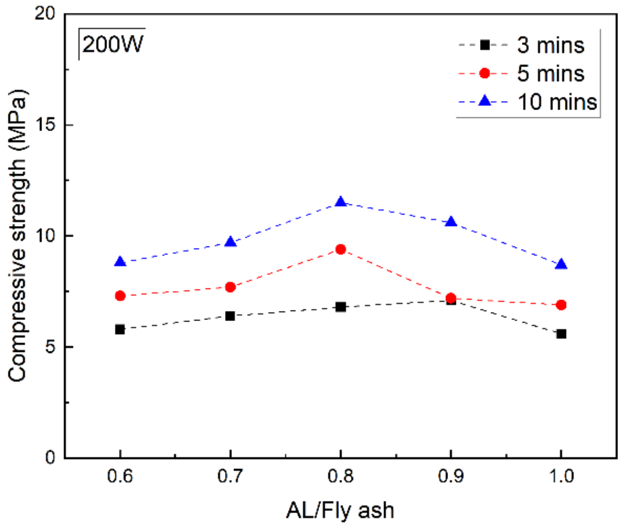


Fig. 5. Relationship between AL/FA and compressive strength of geopolymer concrete cured in the microwave at power level of 200 W.

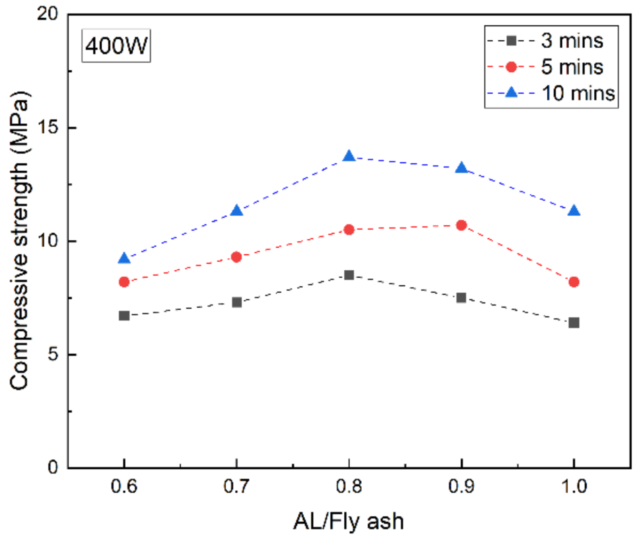


Fig. 6. Relationship between AL/FA and compressive strength of geopolymer concrete cured in the microwave at power level of 400 W.

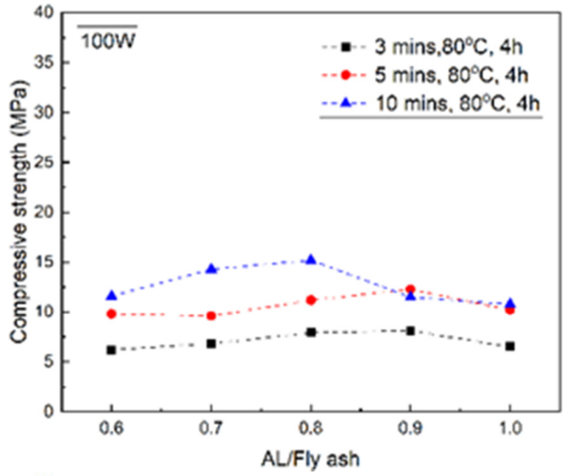
As can be seen in Figure 6, the specimens cured at 400 W exhibited the same behavior with those cured at 100 W and 200 W, with compressive strength increasing as the AL/FA ratio rose from 0.6 to 0.8. Additionally, at a ratio of 0.9, the compressive strength of the mixtures cured for 5 min kept going up, while the strength of the other specimens decreased. When the AL/FA ratio changed to 1.0, all specimens' compressive strength declined. In this case, the highest compressive strength value was 13.7 MPa, at a ratio of 0.8, with a 10-min curing.

From these findings, it is evident that the longer curing periods resulted in higher compressive strength, while strength decreased as the AL/AF ratio approached 1.0. The highest compressive strength was achieved at an AL/FA ratio of 0.8 with a 10-min curing period at 400 W. To further optimize performance and meet design strength requirements, the effects of a hybrid curing method were evaluated combining microwave and oven.

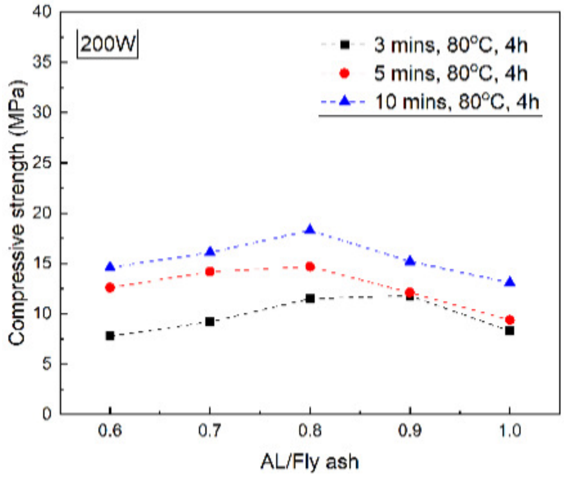
C. Influence of Alkaline Liquid/Fly Ash Ratio on Compressive Strength of Geopolymer Concrete Cured by the Hybrid Microwave-Oven Method

The effect of a hybrid curing method combining microwave and oven was evaluated conducting a series of tests. Mixtures GM1, GM2, GM3, GM4 and GM5 were prepared with six modes of curing procedures, as presented in Figure 2. The test results are displayed in Figures 7 and 8.

(a)



(b)



(c)

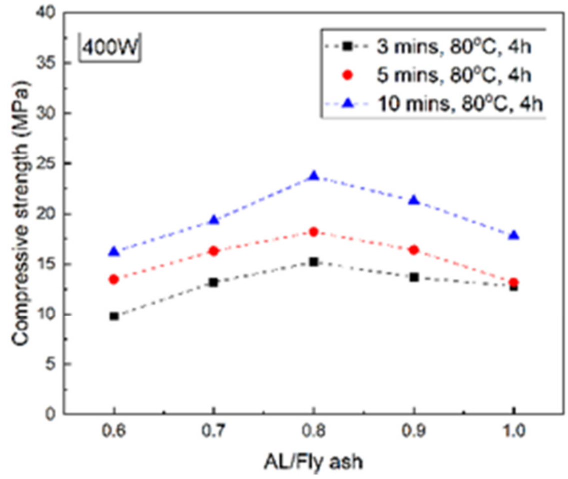
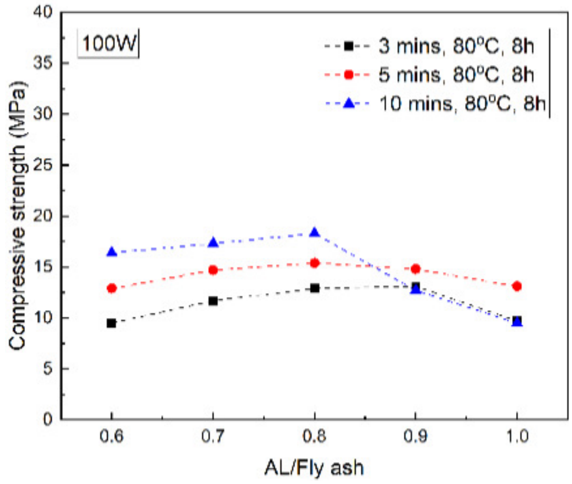


Fig. 7. Relationship between AL/FA and compressive strength of geopolymer concrete cured in mode 1, 2, and 3 of hybrid curing method.

(a)



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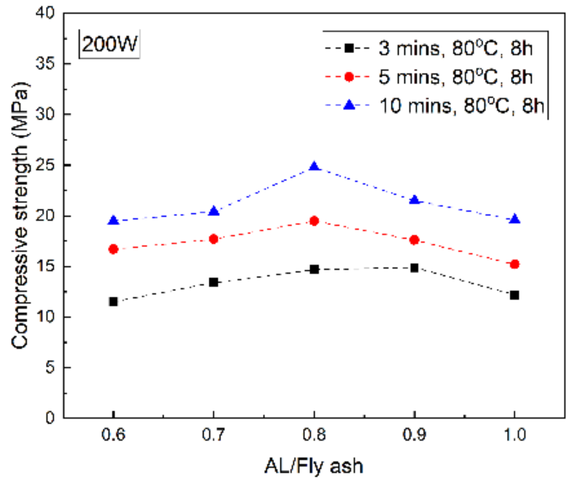

(c)

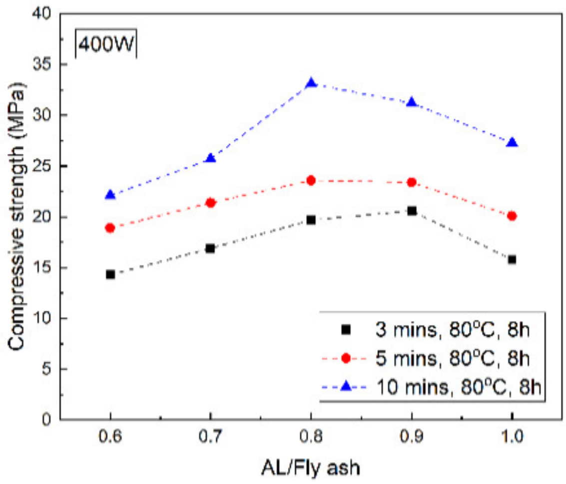

Fig. 8. Relationship between AL/FA and compressive strength of geopolymer concrete cured in mode 4, 5, and 6 of hybrid curing method.

Figures 7(a), 7(b), and 7(c) illustrate the compressive strength of specimens that were first cured in a microwave (at power levels of 100 W, 200 W, and 400 W for 3, 5, and 10 min) and then in an oven (at 80 ^{o}C for 4 hours). In mode-1 curing, the highest strength value was 15.2 MPa, which was 9.4% higher than that of the specimens cured solely in an oven under the same conditions, and over 80% higher than those cured only in a microwave at 100 W. Similarly, in modes 2 and 3, the maximum strength values were 18.3 MPa and 23.7 MPa, respectively, 59.1% and 73% higher compared to the microwave curing at 200 W and 400 W.

Figures 8(a), 8(b), and 8(c) depict the compressive strength of specimens cured in modes 4, 5, and 6 of the hybrid curing method. It is evident that the maximum values of FA-based geopolymer concrete are 18.3 MPa, 24.8 MPa, and 33.1 MPa for modes 4, 5, and 6, respectively. By comparison, while the curing conditions in the microwave remained unchanged, the curing period in the oven changed from 4 to 8 hours, and the compressive strength increased by 20.4% to 39.7%. Longer curing periods resulted in higher compressive strength. The highest compressive strength value in the hybrid curing method was 33.1 Mpa, while the highest one in the oven was 30.2 MPa. This finding indicates that the utilization of the hybrid approach can enhance the compressive strength of FA-based geopolymer concrete.

IV. CONCLUSIONS

The aim of this study is to evaluate the compressive strength of Fly Ash (FA)-based geopolymer concrete cured under three different conditions: oven, microwave, and hybrid method. The key findings from this experiment are summarized as follows:

- In the case of oven-curing, the compressive strength increased as the Alkaline Liquid (AL)/FA ratio changed from 0.6 to 0.8, while at the ratio of 1.0, the compressive strength of all specimens decreased. The mixture with an AL/FA ratio of 0.8 cured at 80 °C for 16 hours was the optimal for achieving maximum compressive strength (30.2 MPa).
- When the FA-based geopolymer concrete was cured in a microwave, the higher energy levels and longer curing periods resulted in higher compressive strength values.
- The hybrid curing method –a combination between microwave and oven curing- demonstrated the best results. The maximum compressive strength was 33.1 MPa, which was 9.6% higher than that cured in the oven.
- The hybrid curing method required shorter time to produce high compressive strength compared to traditional techniques.

Further research on the hybrid curing method is needed to enhance the properties of geopolymer concrete as a sustainable and innovative material in the construction industry.

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