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Investigation of the Compressive Strength of Fly Ash and GGBFS-Based Geopolymer Concretes According to Local Materials and Curing Conditions in Southern Iraq

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Abstract: Geopolymer concrete is still a new construction material in Iraq and needs tremendous research to get more information about the production techniques. This research showcases the characteristics of geopolymer paste produced by treating low-calcium fly ash (FA) and ground granulated blast-furnace slag (GGBFS) with alkaline solution as activa tor. Using GGBFS and FA is not just for sustainable construction, but also for decreasing CO2 emissions from Portland cement usage. The impact of GGBFS and FA on the resistance to compression of geopolymer samples was assessed. T he solution of alkaline activator utilized consists of sodium hydroxide (NaOH) at concentrations of (8-10) M along with sodium silicate (Na2SiO3) with two types of curing (oven at 60°c and Laboratory curing). A test was conducted to mea sure the compressive strength after seven, twenty-eight and ninety days. For geopolymer concrete made with fly ash an d GGBFS 8M (Laboratory curing), and GGBFS 10M (Laboratory curing and oven at 60°C) the compressive strength was (15.43, 24.20, 43.76 and 43.05) MPa respectively for seven days, (20.15, 27, 52.06 and 46.36) MPa for twenty-eigh t days respectively and (20.9,29,54.19 and 47.01) for ninety days respectively.The ratios of compressive strength at 7 da ys to 28 days were approximately 76.57%, 89.62%, 84.05%, and 92.86% for geopolymer concrete made with fly ash a nd GGBFS 8M (Laboratory curing), and GGBFS 10M (Laboratory curing and oven at 60°C) the compressive strength. Based on both practical application and strength points of view its clearly that the geopolymer mixture of GGBFS (10 M) at laboratory curing is the most suitable mixture to be used in southern of Iraq especially at summer season.

Keywords: Geopolymer concrete; Fly Ash; Ground Granulated Blast-Furnace Slag; Laboratory curing; Oven curing

1. Introduction

The most popular material for construction is concrete. Concrete is a mixture of Portland cement aggregates and water and demand for it will rise in the future due to infrastructure developments increased use of it [1]. The manufacture of cement produces carbon dioxide (CO2) into the atmosphere. Thus, traditional concrete affected life and safety i.e. the environmental pollution [2] Therefore, many researchers studied the concrete production by using environmentally friendly materials to replace the cement such as fly ash, metakaolin, and rice husk ash [3,4,5,6] Geopolymer concrete is more durable than normal concrete [7]. Wallah, and Rangan founds that the geopolymer concrete has a high compressive strength, low shrinkage, low creep, and excellent resistance for sulphate [4]. Moreover, geopolymer has significant qualities like quick setting with high early strength low production costs and low energy consumption resulting in little CO2 emission [8]. Geopolymer demonstrated a high potential in the fields of infrastructure and construction. It was also discovered that geopolymer possessed excellent fire resistance and high mechanical performance [9]. Thus, geopolymer concretes development and application are crucial for protecting the environment. The findings also indicated that a higher percentage of slag results in greater compressive strength after 7 days [10]. incorporating GGBFS as a partial replacement for FA enhances the properties of geopolymer concrete in ambient conditions [11].

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Combining slag and fly ash can improve the engineering characteristics and longevity of geopolymer concrete [12]. Incorporating GGBFS in geopolymer concrete as a replacement of fly enhances the structural characteristics and provides a variety of cementitious materials sources [13]. According to available literature their numerous studies to production geopolymer concrete by using, fly ash [26,30], GGBFS [27,28,29]. It was discovered that the GPC strength of compressive rise with use GGBFS with molarity (10) M in the mixes. Because of the high calcium content in GGBFS, it led to the creation of C-S-H gel which helped enhance the progress in building strength geopolymer specimens [23]. The strength development is also influenced by the concentration of the alkali solution. Budh and Warhade found that higher molarity leads to a rise in the strength of compressive [24]. Enhancing the creation of geopolymeric bonds is achieved by releasing Si and Al from the silica-alumina source using alkali hydroxide. Without the presence of an alkali hydroxide solution, the paste will become overly thick, fail to harden, and the samples will lack strength [25]. Supraja& Rao. Used GGBFS replaces Portland cement with varying NaOH molarities (3, 5, 7, and 9) under different curing conditions (sunlight and oven). Results show that higher NaOH molarity increases compressive strength. However, significant strength gains are not observed after three days. Oven curing yields superior compressive strength compared to sunlight curing, though the latter is more convenient [32]. Singh et al, researchers discovered that GPC made from FA has superior resistance to sulfate and acid attacks compared to conventional concrete [33]. Nguyen& Castel, tested physical and durability properties, shrinkage, compressive strength, and setting time were assessed through multiple trials with GGBFS-FNS combinations and various chemical admixtures. Promise was demonstrated by the geopolymers as eco-friendly materials for engineering applications, especially in harsh environments. Compressive strengths exceeding 30 MPa were achieved by the geopolymer mortars after 28 days [34]. Nath et al., This study investigates low calcium fly ash-based geopolymer concrete cured at ambient temperature (23°C) without additional heat. Results indicated that additives significantly improved early-age properties, reducing setting times and improving the strength under compression for early de-moulding. The findings suggest that effective geopolymer mixtures can be designed for ambient curing using low calcium fly ash and additives [35]. Rangan, B. V. Presented a comprehensive summary of the extensive studies conducted on fly ash-based geopolymer concrete. Test data are used to identify the effects of salient factors that influence the properties of the geopolymer concrete in the fresh and hardened states. These results are utilized to propose a simple method for the design of geopolymer concrete mixtures. Test data of various short-term and long-term properties of the geopolymer concrete are then presented [36]. The research examines the influence of various parameters, particularly the molarity of NaOH and curing conditions, on the qualities of geopolymer concrete made from FA and (GGBFS).Increasing the NaOH molarity typically enhances the concrete's compressive strength, as higher molarity solutions facilitate the dissolution of aluminosilicate substances, resulting in improved geopolymerization and a denser microstructure. Geopolymer concrete generally exhibits greater compressive strength when subjected to elevated temperature curing. Heat curing accelerates the geopolymerization process, leading to a more robust and durable material. Although ambient curing is more feasible for on-site applications, it usually yields lower compressive strength compared to heat curing. Nevertheless, optimizing the mix design and curing duration can still produce satisfactory results. These findings indicate that both NaOH molarity and curing conditions are critical in determining the mechanical properties of geopolymer concrete. Adjusting these parameters can help achieve the desired strength and durability for specific applications., aiming to identify the optimal mix of ingredients. The physical and mechanical properties were evaluated at 7, 28, and 90 days. This research project is dedicated to the development of environmentally sustainable concrete. The focus is on optimizing the production process under the unique ambient conditions prevalent in southern Iraq. By leveraging local materials and innovative treatment methods, the research is focused on minimizing the environmental impact of concrete production while maintaining or enhancing its structural properties. The study will explore various aspects of concrete production, including the selection of eco-friendly raw materials, the formulation of concrete mixes, and the application of advanced curing techniques. The specific ambient conditions of southern Iraq, such as temperature and humidity, will be taken into account to ensure the feasibility and effectiveness of the proposed solutions. The ultimate goal is to aid in the development of the construction sector by providing a sustainable alternative to traditional concrete, thereby supporting environmental conservation efforts and promoting green building practices in the region.

2. Methodology

2.1 Materials

2.1.1 Fine Aggregates

The fine aggregates in this study are natural sand (maximum size = 4.75 mm) from Basra area southern Iraq. which corresponds to the Iraqi Standard Specification No. 45/1984 zone 2 [14].

2.1.2 Coarse Aggregate

Fig. 1 lists the characteristics of coarse aggregate that meet the Iraqi Standards requirements IQS 45-1984[14].

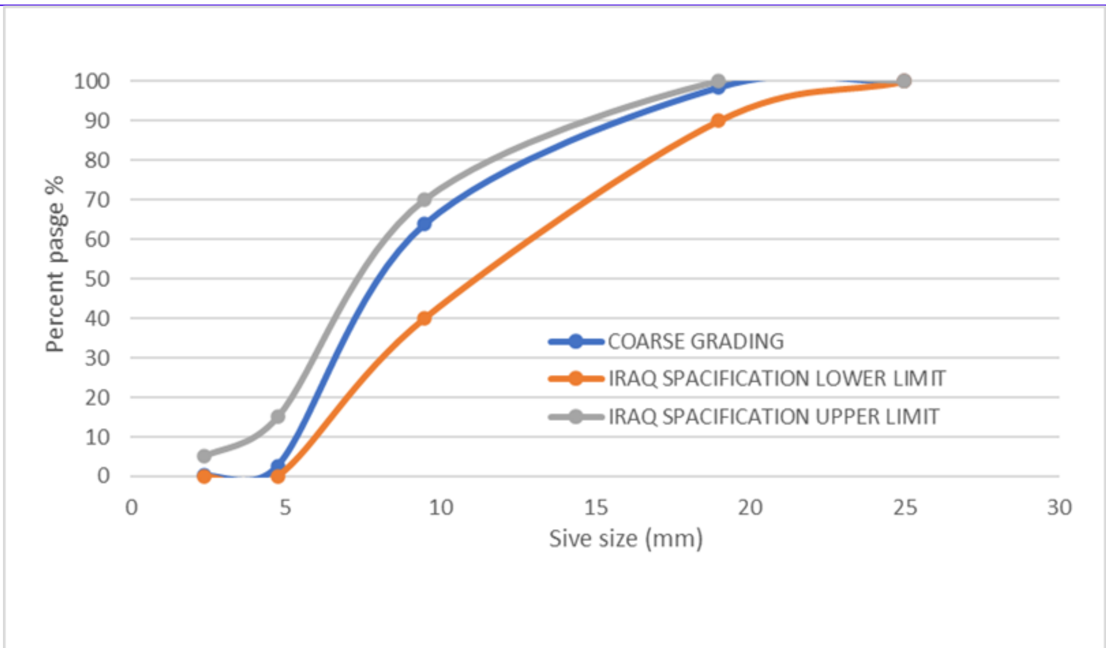

Fig. 1. Grading Curve for coarse aggregate.

2.1.3 Fly Ash (FA)

Fly ash, a by-product of coal-fired power plants, is extensively utilized as a cost-effective substitute for a portion of OPC in standard concrete mixes. It is collected globally from these power plants for incorporation into concrete mixtures. The production process involves grinding coal into a fine powder through a series of mills. This powder is then combusted in a boiler to produce steam for electricity generation. During combustion, the minerals in the coal fuse to form spherical particles with a glassy alumina-silicate structure, which are subsequently collected by precipitation downstream of the boiler [31]. Fig. 2 illustrate this process. FA in fig. 3 used in this current research satisfies the requirements of (ASTM C618,2015) [15] in terms of both its chemical composition and physical attributes, Table 1.

Table 1. Physical properties and Chemical analysis of FA.

Oxides	Chemical composition Content %	Requirements of FA (ASTM C618-15)[15]
Chemical composition		
SiO_2	88.15	≥ 70
Fe_2O_3	1.6	
Al_2O_3	4.24	
CaO	1.82	
MgO	0.18	
K_2O	0.51	
Na_2O	0.08	
SO_3	0.02	Max. 4%
L.O.I	3.23	Max. 10%
Physical properties		
Specific surface area m m2/g	12-18	
Specific gravity	2.7	

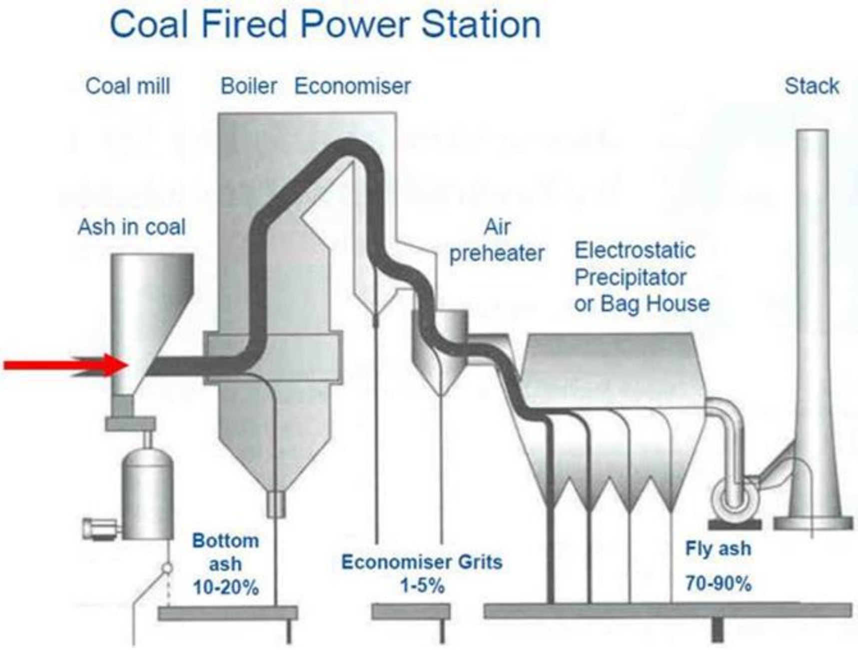

Fig. 2. Fly Ash Retrieval Process [31].

Fig. 3 Fly Ash.

2.1.4 Ground Granular Blast Furnace Slag (GGBFS)

GGBFS is a commercial by-product commonly incorporated into GPC mixes. It is primarily used to reduce thermal hydration, enhance resistance to abrasion from groundwater, and combat various environmental conditions. GGBFS is produced during the steelmaking process, where iron ore, coke, and a flux are heated to their melting point in a blast furnace. After the melting process is complete, the molten material, which contains aluminates and silicates from the coke and ore ash, is rapidly cooled to form blast furnace slag. This slag is then ground into a fine powder for use in concrete mixes [31]. The GGBFS in fig. 4 used in the present work satisfies the requirements of (ASTM C989-2010) [16] in terms of both its chemical composition and physical attributes, Table 2.

Table 2. Physical properties and Chemical analysis of GGBFS.

Chemical composition		
Oxides	Chemical composition Content %	Requirements of GGBFS (ASTM C989-10)[16]
SiO_2	35.9	
Fe_2O_3	0.6	
Al_2O_3	8.4	
CaO	37.9	
MgO	8.9	
K_2O	0.7	
Na_2O	0.3	
SO_3	0.7	
L.O.I	0.9	
Sulfide sulfur (S)	0.5	Max.2.5%
Physical properties		
Specific surface area mm2/g	450	
Specific gravity	2.98	

Fig. 4. GGBFS.

2.1.5 Superplasticizer (SP1)

TOPFLOW SP 603 was used which is agreed with ASTM C494 Types A, B, D, F and G [17]. The dosage is ranged from 0.5 to 3.0 L per 100 kg of the binder. Table 3 demonstrates the superplasticizers characteristics (SP1).

Table 3. superplasticizers characteristics (SP1).

Property	Description
Color	Dark brown / black liquid
Specific gravity	1.21 at 25° C±2°C
Air entrainment Maximum	1%
Chloride content	Nil
Nitrate content	Nil
Freezing point	0° C

2.2 Experimental Work

The program being tested includes four different methods of making GPC. The initial study looked into the potential of utilizing FA (8M) in Laboratory curing, the second method involved researching the feasibility of using GGBFS (8M) in Laboratory curing, the third experiment resulted in the using GGBFS (10M) in oven curing and the fourth method was using GGBFS (10 M) in laboratory curing. A comparison was created by analyzing in their outcomes. In general, the examination focused on the compressive strength.

2.2.1 Proportions of mixture in Geopolymer Concrete

To get the closest approximation to reality one of the most popular weight ratios for mixing (1:1. 5:3) is used. The masses of the gravel sand and binder in the mix are 1200, 650 and 400 kg per cubic meter respectively. The ratio of water to binder is 0:125 (plus superplasticizer). The proportions of the geopolymer concrete mixture are listed in Table 4.

Table 4. Mixture proportions of geopolymer concrete

For Fly Ash and ground granular blast furnace slag (10) molar	
Materials	Mass (kg/m3)
Coarse aggregates	1200
Fine aggregates	650
Fly ash or ground granular blast furnace slag	400
Sodium hydroxide (10)M	23
Sodium silicate solution	110
Super plasticizer	12
Extra water	50
For ground granular blast furnace slag (8) molar	
Coarse aggregates	1200
Fine aggregates	650
Fly ash or ground granular blast furnace slag	400
Sodium hydroxide (8)M	19
Sodium silicate solution	200
Super plasticizer	12
Extra water	73

2.2.2 Manufacturing Geopolymer Concrete

The NaOH solution is made up of sodium silicate and sodium hydroxide. Sodium hydroxide is in flake form with a purity of over 98%, and it can be dissolved in water that has been filtered. Alkaline liquid consists of a blend of NaOH solution and Na2SiO3 solution. The combination of the two solutions to create alkali fluid should be done no less than 24 hours in advance [18]. Additional water is commonly added to GPC with varying amounts for enhanced workability. Additionally, the superplasticizer (high-range water reducer) can be utilized to enhance the strength. The superplasticizer is mixed with more water until a uniform solution is obtained. The mixing process of GPC can be carried out by utilizing the conventional methods employed in making regular concrete [19]. Initially, a dry mixture of all materials (FA or GGBFS), fine aggregate, and coarse aggregate is blended in the concrete mixer for about three minutes. The alkaline liquid, superplasticizer, and additional water were blended together for around two minutes. Following this, the wet ingredients were incorporated into the dry elements and blended together for a duration of four minutes within the cement mixer [18]. The samples were molded into 9 cubes for each mix fig. 5. After that, the compaction is done by hand. Following the casting process. Two curing methods were employed: Laboratory curing and heating curing inside a furnace at 60°C for 24 hours.

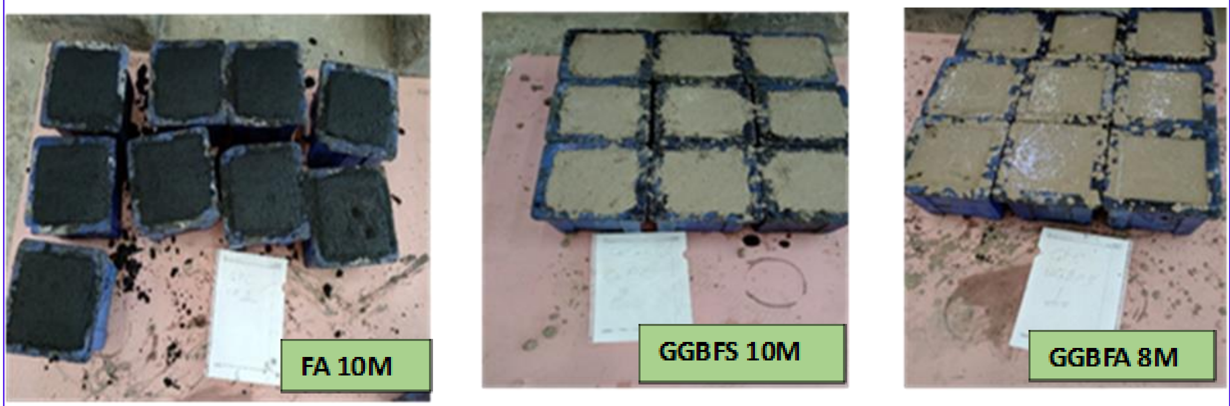

Fig. 5. Casting for specimens.

3. Results and Discussion

The Compressive Strength test was carried out in accordance with (BS. 1881: Part 116: 1989) [20]. The hydraulic concrete compression device is utilized for testing the (150*150*150) mm cube samples. The test was on the 7th, 28th and 90th days according to international references [9]. This research examines various curing methods and molarities to find out the perfect condition for geopolymer concrete. For FA (10M) and GGBFS (8M,10M) the curing mothed was laboratory curing as in Fig 6, .for GGBFS (10 M) the curing mothed was in oven at 60°C as in fig. 7. Table 7, and fig. 8 displays compressive strength of GPC. Fig. 8 illustrates the correlation between the compressive strength geopolymer materials in the mixes at the curing ages of 7, 28 and 90 days.

The compressive strength values for 7 days were 15.43 MPa, 24.2 MPa, 43.76 MPa, and 43.05 MPa for FA (10M) Laboratory curing, GGBFS (8M, 10M) Laboratory and oven curing, and GGBFS (10M) Laboratory curing, respectively. These values increased in 28 days to 20.15 MPa, 27 MPa, 52.06 MPa, and 46.36 MPa, respectively. The ratios of compressive strength at 7 days to 28 days were approximately 76.57%, 89.62%, 84.05%, and 92.86%. This indicates significant strength development over time, particularly for GGBFS specimens. The observed increase in compressive strength over time can be attributed to several factors. For materials such as fly ash FA and GGBFS, pozzolanic reactions significantly contribute to strength gain. These reactions occur between the silica in the pozzolans and the calcium hydroxide released, forming an additional calcium silicate hydrate (C-S-H) gel. Laboratory and oven curing provide controlled environments that optimize pozzolanic reactions, leading to more efficient strength development. The specific properties of FA and GGBFS, including their fineness and chemical composition, play a crucial role in the rate and extent of strength gain. The average densities for 7 days were 2257.43 kg/m³, 2343 kg/m³, 2354 kg/m³, and 2363.66 kg/m³ for FA (10M) Laboratory curing, GGBFS (8M, 10M) Laboratory and oven curing, and GGBFS (10M) Laboratory curing, respectively. These values slightly changed in 28 days to 2225 kg/m³, 2336.3 kg/m³, 234.3 kg/m³, and 2391.60 kg/m³. The densities for 90 days were 2227.6 kg/m³, 2332.6 kg/m³, 2336 kg/m³, and 2375.12 kg/m³, showing minor variations over time. The FA specimen was difficult to remove from the mold after 7 days, likely due to ongoing reactions involving free lime. In contrast, GGBFS (8M and 10M) specimens did not exhibit this issue, suggesting a more stable curing process. The results indicate that GGBFS-based geopolymer concrete, particularly with 10M concentration and laboratory curing, shows superior compressive strength and density characteristics over time. This makes it a promising material for construction, especially in regions with high temperatures like southern Iraq. However, the performance of fly ash concrete is influencing by many factors such as, the type of fly ash (physical & chemical properties), the level of replacement used, and the quality of the concrete [21]. In the GPC, there are several factors that affect the compressive strength. These factors include the molarity of the alkali liquid, the ratio of the pozzolanic material, the percentage of amorphous silica and alumina found in the pozzolanic material, and the curing temperature, The relationship between the pozzolanic material and alkaline liquid is similar to the ratio of water to cement in the traditional concrete formula [22].

Fig. 6. Laboratory curing.

Fig. 7. Inside furnace at 60°C.

Table 7. Strength under compression for all combinations.

No.	Mix designation	Curing system	Molarity	Compressive strength (MPa)		
				7days*	28 days*	90 days*
1	FA	Laboratory curing	10	15.43	20.15	20.9
2	GGBFS	Laboratory curing	8	24.2	27	29
3	GGBFS 2	Inside furnace at 60°C	10	43.76	52.06	54.19
4	GGBFS3	Laboratory curing	10	43.05	46.36	47.01

*Average of three test result

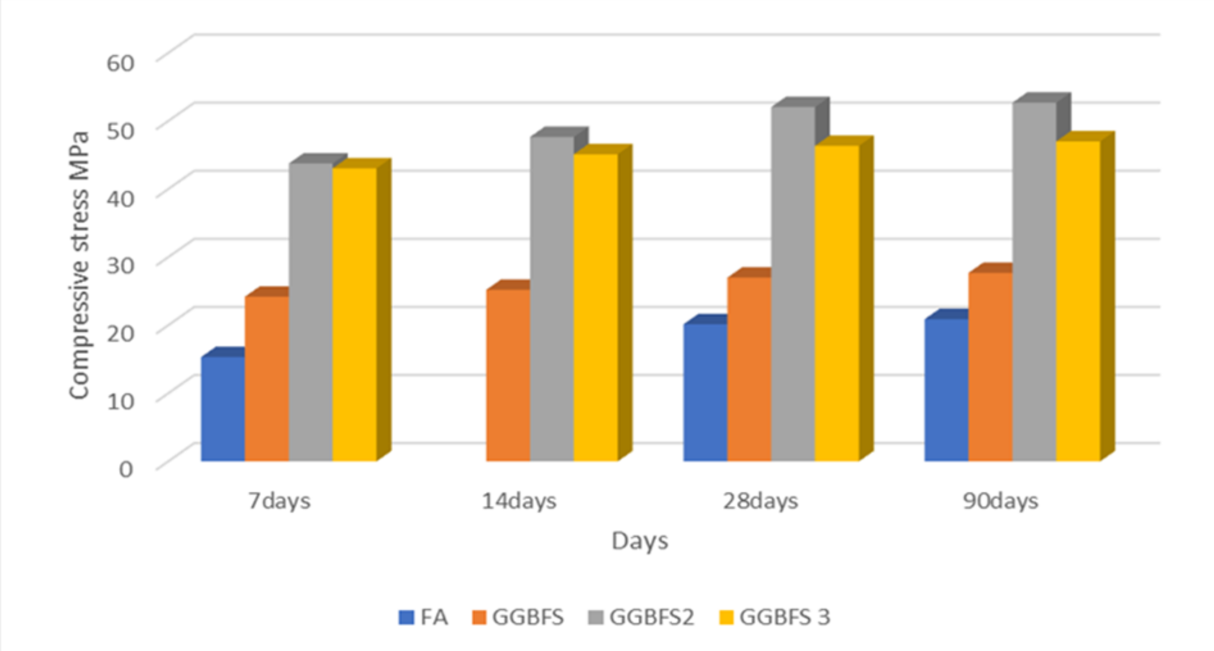

Fig. 8. Compression strength of geopolymer cubes concrete.

4. Conclusions

The conclusions drawn from the experimental results are as follows:

Geopolymer Concrete as a Substitute: Geopolymer concrete made with FA and GGBFS is a robust alternative to conventional concrete, offering superior properties and sustainability.Impact of Curing Methods: Heat curing significantly enhances the compressive strength of GPC, achieving an 89.05% increase over laboratory curing in 28 days.Resistance and Density: The resistance of GPC reaches 76.5% for FA and up to 80% for GGBFS. The density of GPC made with FA (10M) is approximately 6.62% lower than that made with GGBFS (10M) after 90 days of laboratory curing.Optimal Strength Conditions: Using GGBFS (10M) for GPC and curing it at 60°C results in higher compressive strength. This mixture, cured in a laboratory, is ideal for southern Iraq's summer conditions, achieving 47.01 MPa compressive strength, 2.89 MPa splitting strength, and 2357.12 kg/m³ density at 90 days.

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