

# Multi-Objective Optimization of Geopolymer Cement Block Parameters Using Bentonite and Fly Ash

Bagirisoko Edison<sup>1\*</sup>, M. Achyutha Kumar Reddy<sup>2</sup>, V. Sree Lakshmi<sup>3</sup>

## Abstract

Presently, geopolymer blocks are being produced by using industrial by-products like fly ash. This study focuses on the development of geopolymer cement blocks using the composition of bentonite and fly ash. The specific objective is to examine and optimize the geopolymer cement block parameters using a novel composition. The oxide ratio, alkali activator ratio, and molarity are considered variables. In contrast, the responses are considered as flow table, fresh density, compressive strength, compressive strength - temperature curing, density and water absorption. The mix matrix design was generated upon fixing the lower and upper limits of variables using response surface methodology (RSM). The laboratory experiments were conducted as per the mix matrix design to obtain the responses. The RSM model was developed using the values of responses for all mixes; analysis was also performed to verify the significance. It was found that all terms in the model were significant, showing a confidence level of more than 85 per cent. Furthermore, multi-objective optimization was also performed for the specified variables with a desirability of 1.0. At the outset, the development of geopolymer cement blocks was confirmed.

**Keywords:** Geopolymer, bentonite, fly ash, oxide ratio, alkali activator, molarity, response surface methodology (RSM)

## INTRODUCTION

Typical Cement concrete has long been made using Portland cement as a binding agent. Its energy-intensive production method releases greenhouse gases into the atmosphere, which pollutes the environment. The literature claims that factories that produce cement account for close to 7% of global CO<sub>2</sub> emissions. The method used to compare greenhouse gas emissions, which range from 0.66 to 0.82 kg of CO<sub>2</sub> emitted for every kilogram produced, based on their ability to cause global warming. [1], [2]. The use of alkali-activated materials as Portland cement substitutes has received much interest as a

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means of minimizing the detrimental effects of the cement industry on the environment [3]. One of the main chemical differences between the Portland cement system and the alkali-activated system is the aqueous solution. The aqueous solution used to make Portland cement is water, and its pH starts at neutral and progressively increases to 12–13 with increasing solid dissolution [4]. Though our understanding of the processes governing the alkali activation process has greatly expanded over time, there are still a lot of unanswered questions [5]. In addition to cement paste, the other binders, like fly ash and GGBFS, can be used with an alkaline activator to create a geopolymer mortar. A mortar that uses natural materials and components as a binder is called geopolymer mortar. Where natural materials with high silica and alumina oxide

contents are utilized [6], one waste product from thermal power plants is fly ash. It is one of the pozzolanic materials that is used in the construction industry most frequently [7]. When producing geopolymer binder and concrete composites, fly ash is the most commonly used aluminosilicates material, either completely or partially replacing regular Portland cement [8].

Previous studies have suggested that more than 800 million tons of fly ash (FA) are produced annually worldwide. Furthermore, it is anticipated that the majority of the FA produced will be disposed of in landfills, which fuels concerns about environmental damage and the loss of valuable land.[9]. Fly ash has caused a significant threat to the ecological environment because of the restricted storage in locations and disposal techniques[10]. The use of fly ash in concrete can drastically reduce its durability, leading to early concrete degradation and the need for repairs. [11]. Fly ash will not be produced after the thermal power units are permanently shut down. Therefore, the development of substitutes for the pozzolanic materials produced from industrial wastes is required.

More research is required on alternate materials to fly ash. Bentonite is a clay-based substance that has enormous global resource availability. It exhibits pozzolanic behavior since silicon dioxide ( $\text{SiO}_2$ ) is available. Bentonite, a mineral admixture (clay), has several uses across a range of industries. Among the most common uses for bentonite are as drilling fluids, absorbents, pelletizing iron ore, and manufacturing bonding[12]. A pozzolanic with cementitious qualities, when combined with cement or lime, should include at least 70% of the weight of the unit sample in silicon dioxide ( $\text{SiO}_2$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), and iron oxide ( $\text{Fe}_2\text{O}_3$ )[13]. Comparing a traditional concrete mixture with OPC as the only binder to one with bentonite partially replacing OPC yields a higher proportion of siliceous and aluminous chemicals after the pozzolanic reactions [14]. Bentonite strengthens mortar and keeps it from splitting once it dries, giving mortar a significant boost in durability. Pozzolanic materials in different mineral compositions have a significant impact on the mortar's functionality, robustness, and longevity [15]. In India, Gujarat accounted for 97% of the total value of bentonite production, with Rajasthan accounting for the remaining 3% [16].

Therefore, research on the bentonite treatment procedure is required to determine the influence of bentonite on construction. [17]. Few studies showed that the increased  $\text{SiO}_2$  content makes it challenging to produce geopolymer binders using bentonite alone. Bentonite has an average particle size of approximately  $4.32\ \mu\text{m}$  [18]. The majority of authors noted that the addition of bentonite resulted in decreased strengths at early curing ages (3, 7, and 28 days), with superior performance exhibited at later curing ages (56 & 90 days) in comparison to control concrete.[19].

The chemical reaction of inorganic particles often creates the novel building material known as geopolymer binder, and it has the potential to cut greenhouse gas emissions by as much as 80% [20]. Inorganic polymers, known as geopolymers, are similar to ceramics and are often produced at temperatures lower than  $100\ ^\circ\text{C}$ . They are made up of networks or chains of mineral molecules connected by covalent connections. Through polymerization, fly ash and other pozzolanic materials are activated with an alkali activator, creating an inorganic binder. [21][22]. Energy consumption in the calcination of cement, waste disposal, and resource extraction is decreased by using these industrial wastes. [23]. Geopolymers are new engineering materials that have the potential to play a significant role in the development of ecologically friendly building products and construction. [24].

The process of geo-polymerization creates a three-dimensional polymeric chain by reacting aluminosilicates with a strong alkaline media, such as NaOH, KOH, or their combination. Geopolymers can be potentially viable substitutes for Portland cement because of their low carbon dioxide emissions and mostly waste composition (fly ash, bottom ash, slag, kaolin sediments, etc.)[25]. The ingredients utilized to create geopolymers in engineering and research are often natural minerals like clay and metakaolin or industrial aluminium-silica wastes like fly ash, rice husk ash, and blast furnace slag[26]. Combining sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) with sodium hydroxide (NaOH) is a typical alkaline activator

used in geopolymerization [27]. Systems activated by sodium silicate have been studied and shown to be capable of producing very high strengths [28]. Low-calcium fly ash must be activated by an alkaline solution to form polymeric Si-O-Al linkages in order to make a Geopolymer. The usage of geopolymer could result in an 80% reduction in greenhouse gas emissions from the concrete sector [29]. In fly ash-based geopolymer concrete, it appears that increased NaOH content decreased both the amount of free and total chloride infiltration [30]. alumina in bentonite reduces the strength of exothermic reactions and lengthens the setting time [31]. Similar cementitious qualities are provided by low-CO<sub>2</sub> cements, which do not rely on the calcium silicate hydration mechanism. These low-CO<sub>2</sub> cements use an alkali-activation process (based on potassium or sodium) to activate silicon-aluminates [32].

Response surface methodology, or RSM, is a set of statistical and mathematical methods that are helpful for modelling and analyzing situations where the goal is to optimize a response of interest that is influenced by multiple variables. [33]. In RSM, statistical analysis is utilized to establish the relationship, effects, and interaction between factors and responses by connecting each response through a set of related variables.[34].By employing fly ash and bentonite as input variables, a limited body of literature has employed RSM to create model equations that predict the properties of geopolymer binders. A model to forecast the compressive strength of pervious concrete has been created using response surface methodology (RSM) [35]. When it came to multi-variable and multi-objective optimizations, this method was initially presented to identify the intricate relationships in an effort to identify the intended result. [36]. RSM was used by Mohammed et al. to establish a relationship between the independent factors and responses on compressive strength in concrete by using the paper mill as an additive [37].

Numerous investigations into the compressive strength of geopolymer concrete with varying mixing ratios and test parameters have been conducted. Nonetheless, the literature needs to include more study data on geopolymer binders based on fly ash and bentonite as the source materials. Fly ash, fine aggregate, and bentonite were the three precursors used in this work to create geopolymer mortar. The purpose of this research is to evaluate the properties of geopolymer binder using bentonite and fly ash as the source materials and to perform multi-objective optimizations through RSM (Response Surface Methodology) to the geopolymer cement block parameters using bentonite and fly ash as the source materials.

## **MATERIALS AND METHODS**

Fly ash, the waste by-product from thermal power plants, has been utilized, displayed in Figure 1. We used class-F type fly ash from Vijayawada thermal power facility in Vijayawada, Andhra Pradesh, for our work. [38] Table 1 shows the physical characteristics of fly ash. Bentonite used in this research was mined in Tandur, in southern India (17°14'27"N and 77°35'14"E), shown in Figure 2. A muffle furnace was used for the bentonite calcination. [7].the fine aggregate used in this investigation was employed in accordance with the ASTM C33/C33M-18 standard method, displayed in Figure3. [39]. A mixture of sodium hydroxide (NaOH) and sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) silicate was used as the alkaline activator liquid in geopolymerization, mentioned in Figure 4. The molarity of NaOH that was used varied between 8, 12, and 16 M, with a ratio of Na<sub>2</sub>SiO<sub>3</sub> / NaOH varied from 2, 2.3 and 2.6. The Properties of binder materials fly ash and bentonite are shown in Table 2.

### **Mix Proportions**

RSM from Design Expert software version 11 was utilized to design the mix proportioning. The central composite design approach was chosen in order to analyze the outcomes and proportion of the mixes. Bentonite was utilized as a partial substitute for fly ash and alkaline activator (NaOH, Na<sub>2</sub>SiO<sub>3</sub>), which are vital elements that facilitate the dissolution, polymerization, and creation of the geopolymer gel network after the alkaline activation of aluminosilicates precursors. Before importing the existing data, the minimum and maximum values of the variations should be defined.[40]. . The number of experimental mixes should also be specified. The specific ranges of the variables utilized in the experiment are shown in Table 3.



**Figure 1.** Fly ash.



**Figure 2.** Bentonite.



**Figure 3.** Fine aggregate



**Figure 4.** Sodium silicate and Sodium hydroxide pellets.

**Table 1.** The physical characteristics of fly ash.

Properties	Values
Specific gravity	1.975
Fineness modulus	1.195

**Table 2.** Properties of binder materials.

Property/oxide	Formula	Fly ash	Bentonite
Silicon Dioxide	SiO <sub>2</sub>	59.04	51.11
Aluminum Oxide	Al <sub>2</sub> O <sub>3</sub>	34.08	16.38
Iron Oxide	Fe <sub>2</sub> O <sub>3</sub>	2.0	7.65
Lime	CaO	0.22	16.38
Sulphur Trioxide	SO <sub>3</sub>	0.05	-
Magnesium Oxide	MgO	0.43	7.57
Alkalies	Na <sub>2</sub> O	0.5	0.29
Alkalies	K <sub>2</sub> O	0.76	1.34
Phosphorus pentoxide	P <sub>2</sub> O <sub>5</sub>	-	0.29
Manganese dioxide	MnO <sub>2</sub>	-	0.14
Vanadium oxide	V <sub>2</sub> O <sub>5</sub>	-	0.07
Titanium dioxide	TiO <sub>2</sub>	-	1.29
Loss of ignition	LOI	0.63	6.75

**Table 3.** Limitations of the variables utilized in the research project.

Factor	Variables	Lower	Upper
F:1	Oxide Ratio	2.74	4.69
F:2	Alkali Activator Ratio	2	2.6
F:3	Molarity	8	16

The factors influencing the shift in replies were examined using RSM. Using input variables (Oxide Ratio, Alkali Activated Ratio and Molarity), RSM was used to create model equations for response prediction as well as to analyze and investigate the impact of one or more factors on the response. RSM analysis was performed using Design Expert 10 software to create a mixed matrix. Table 4 shows the detailed of mix matrix.

**Table 4.** Mix matrix design.

Run	Mix ID	F:1	F:2	F:3
		<i>OR</i>	<i>AAR</i>	<i>Molarity</i>
1	C-1	3.715	2.3	12
2	C-2	3.715	2.3	12
3	C-3	3.715	2	12
4	C-4	2.74	2	16
5	C-5	2.74	2.6	16
6	C-6	3.715	2.3	12
7	C-7	3.715	2.6	12
8	C-8	2.74	2	8
9	C-9	4.69	2.6	16
10	C-10	4.69	2	8
11	C-11	4.69	2	16
12	C-12	2.74	2.6	8
13	C-13	3.715	2.3	12
14	C-14	2.74	2.3	12
15	C-15	4.69	2.6	8
16	C-16	4.69	2.3	12
17	C-17	3.715	2.3	12
18	C-18	3.715	2.3	12
19	C-19	3.715	2.3	8
20	C-20	3.715	2.3	16

**Table 5.** Combination ratio of all mixes for 1 m<sup>3</sup>.

Mix ID	Fine aggregate	Bentonite	FLY ASH	NA <sub>2</sub> SiO <sub>3</sub>	NaOH
	<i>In Kgs</i>	<i>In Kgs</i>	<i>In Kgs</i>	<i>In liters</i>	<i>In liters</i>
C-1	1408	406.12	165.88	154	66
C-2	1430	390.5	159.5	154	66
C-3	1474	374.88	153.12	132	66
C-4	1452	275	275	132	66
C-5	1430	264	264	176	66
C-6	1408	406.12	165.88	154	66
C-7	1408	390.5	159.5	176	66
C-8	1474	264	264	132	66
C-9	1386	469.04	102.96	176	66
C-10	1452	451	99	132	66
C-11	1474	432.96	95.04	132	66
C-12	1386	286	286	176	66
C-13	1430	390.5	159.5	154	66
C-14	1452	264	264	154	66
C-15	1386	469.04	102.96	176	66
C-16	1430	451	99	154	66
C-17	1452	374.88	153.12	154	66
C-18	1408	406.12	165.88	154	66
C-19	1430	390.5	159.5	154	66
C-20	1452	374.88	153.12	154	66

## **SPECIMEN PREPARATION AND TESTING**

First, the dry materials (fly ash, bentonite and fine aggregate) were manually mixed for two minutes. After that, sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) and sodium hydroxide (NaOH), the alkaline activator, were added and mixed for five minutes to help the geopolymerization process. The solvent was left to stand for roughly 24 hours until it became homogeneous before being used in the mixture. The mortar slurry leaks were prevented by firmly clamping steel moulds. To prevent uneven mortar setting in steel moulds, a small amount of grease was applied on the interior surface prior to pouring mortar into the moulds. After two days, specimens were removed from the moulds and allowed to cure at room temperature for a total of 28 days. In this study, six cubes were prepared for each mixture (70.5\*70.5\*70.5 mm). Both Indian and American standard codes were used for performing all tests. A compressive Strength Test was conducted in order to establish the highest compressive load that geopolymer mortar is capable of supporting before failing. A water Absorption test was conducted to measure the ability of geopolymer to absorb water, which is essential for assessing its resilience to environmental changes and long-term durability. To assess the consistency and workability of mortar, a flow table 5 test was carried out. In every mixture, specimens were examined after twenty-eight days for compressive strength, and other specimens were examined for temperature curing and water absorption. All specimens were tested using a compression testing machine with a maximum capacity of 3000 KN and a loading rate of 1 KN/Sec.

## **RESULTS AND DISCUSSION**

### **Flow Table**

The consistency or workability of the geopolymer was assessed using the flow table test—a flat circular table with a handle for rotation and a mould placed on top. To stop the mortar from sticking to the inside of the mould, a thin coating of oil or grease was applied. The mould was filled with freshly mixed geopolymer mortar and compacted. The mould was carefully lifted once it was filled to allow the mortar to run onto the flow table. The diameter of the mortar was measured and recorded as soon as the mortar stopped moving. Figure 5, shows the flow table results for all mixes. The highest value recorded was on combination C-5—this is due to the highest alkaline activator ratio of 2.6 and the highest molarity of 16. The Increase in fluidity is the result of higher activator concentrations. The lowest value recorded is from combination C-8. Lower fluidity mortar was caused by the lowest concentration of the alkaline activator solution of 2 and the lowest molarity of NaOH, which was 8. Mix design, materials and testing protocols should be the primary cause of poor flow table values in geopolymer mortar. Afterwards, modifications might be implemented to maximize fluidity and fulfil the intended performance specifications.

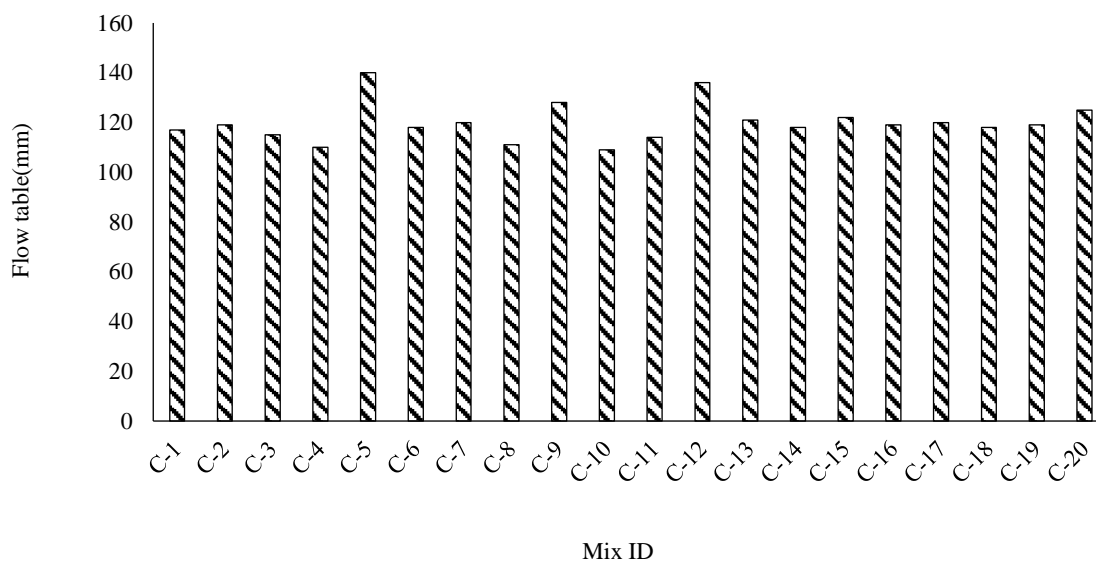
### **Fresh Density of Geopolymer Mortar**

To guarantee consistency and accuracy in the results, it is imperative to follow applicable standards or requirements unique to geopolymer mortar testing. Firstly, Weigh a mould that is empty (M1). After the geopolymer mortar had been mixed, it was poured inside the mould then the weight of fresh geopolymer mortar with mould was recorded (M2). The fresh density of geopolymer has been calculated by this formula  $(M2-M1)/\text{Volume of the mould}$ . As shown in Figure 6, the highest recorded fresh density was on combination C-4; this is due to the highest molarity of an alkaline activator (NaOH), which was 16, and the lowest Alkali Activated Ratio of 2. The lowest fresh density recorded was on combination C-9 because of the highest oxide ratio of 4.69 and the highest alkali-activated ratio of 2.6. The low binder content of fly ash in this mixture caused a less dense matrix with more porosity, which reduced the fresh density of the geopolymer binder.

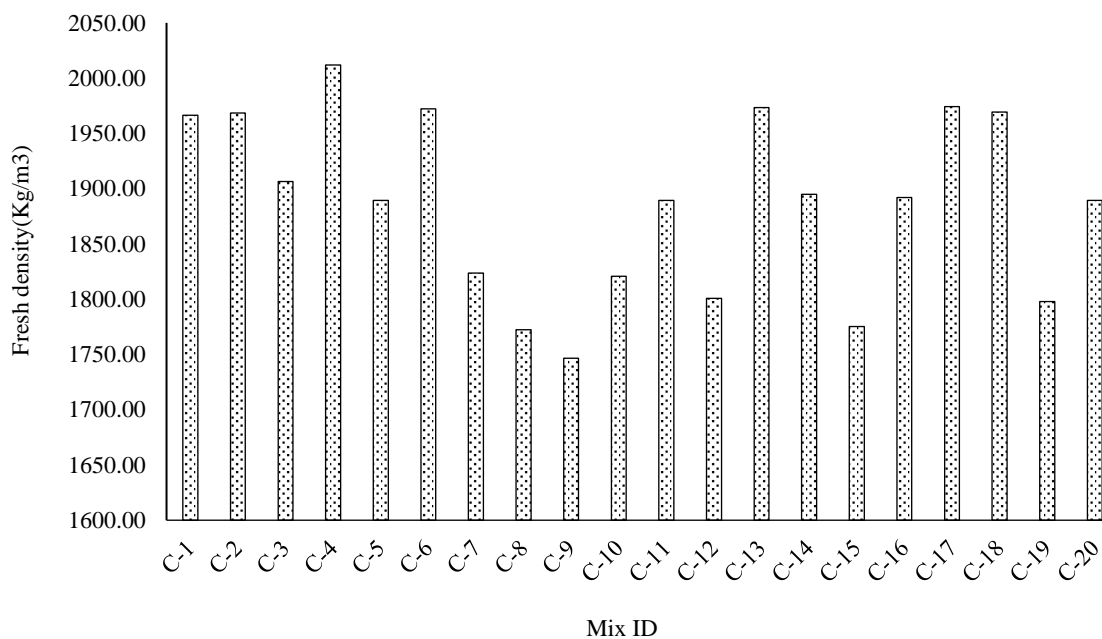
### **Density After Water Curing (Kg/M3)**

Geopolymer mortar samples were cured in water for 24 hours. Samples were cured at room temperature for 28 days before being cured in water. The samples were taken out of the water after the curing time. The weight of each sample was determined using a precise balance. The mass of the samples was expressed in kilograms (kg). The density of mortar cubes was calculated by using the

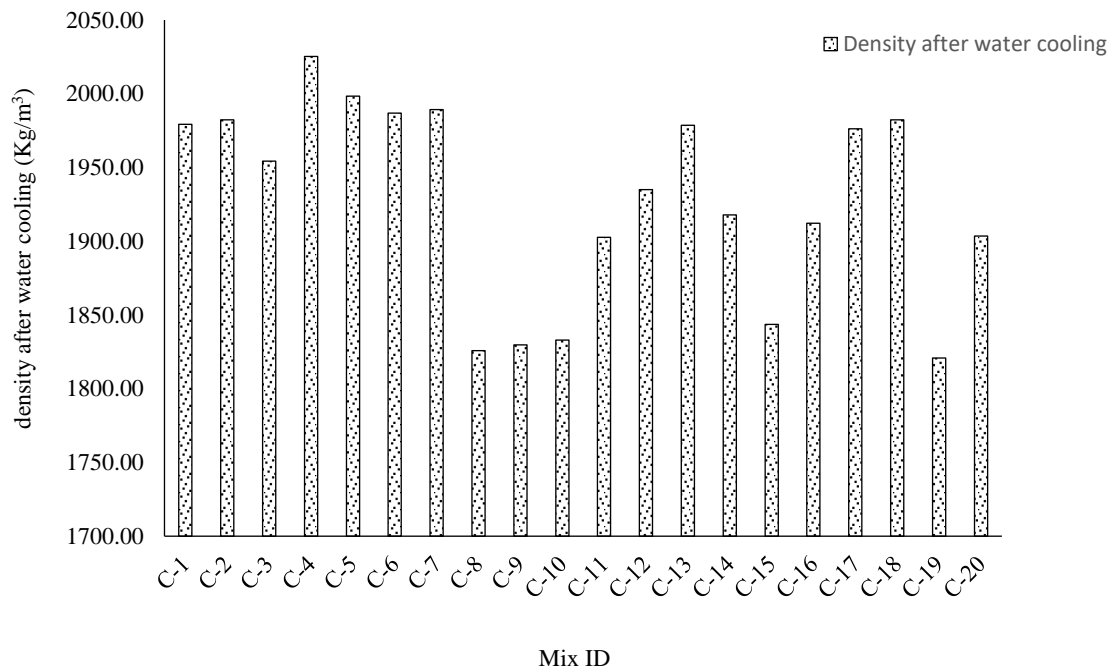
following formula:  $\rho=M/V$  where  $\rho$  is the density,  $M$  is the mass of the sample in kilograms, and  $V$  is the volume of the cube in  $m^3$ . The highest density recorded was on combination 4(C-4) due to the high amount of fly ash in this combination, which has a low calcium concentration but a high silica and alumina content. Because of its glassy nature and high reactivity with alkali activators, fly ash helps to create a denser geopolymer structure. An alkaline geopolymer mortar composed of fly ash and bentonite that has undergone water curing, its density is mostly determined by the chemical reactivity and quantities of the raw components. Figure 7, shows the recorded density after water curing. In order to guarantee accuracy and consistency, the average density of several samples was evaluated.



**Figure 5.** Flow table for all mixes.



**Figure 6.** Fresh density for all mixes.



**Figure 7.** Density after water curing.

### Compressive Strength

The specimen was properly aligned with the loading platens before inserting it into the compressive strength testing machine. In accordance with the applicable standard, the load was applied at a constant pace. Figure 8 shows the recorded compressive strength for all mixes at 28 days. The highest recorded strength was on mix C-8. This is due to the high percentage of fly ash in this mixture, which has a major impact on the compressive strength of geopolymer mortar. By means of the polymerization process, fly ash aids in the formation of a dense and uniform matrix. In general, high-calcium fly ash improves the early strength of geopolymer. The lowest strength recorded was on combination the less strength was impacted by a lower fly ash content in this mix (18% fly ash and 82% bentonite). Bentonite is less reactive than fly ash. It functions more as a filler than a binder, which results in a decrease in compressive strength. But when properly activated, bentonite increases strength by supplying more aluminosilicates for the creation of geopolymers.

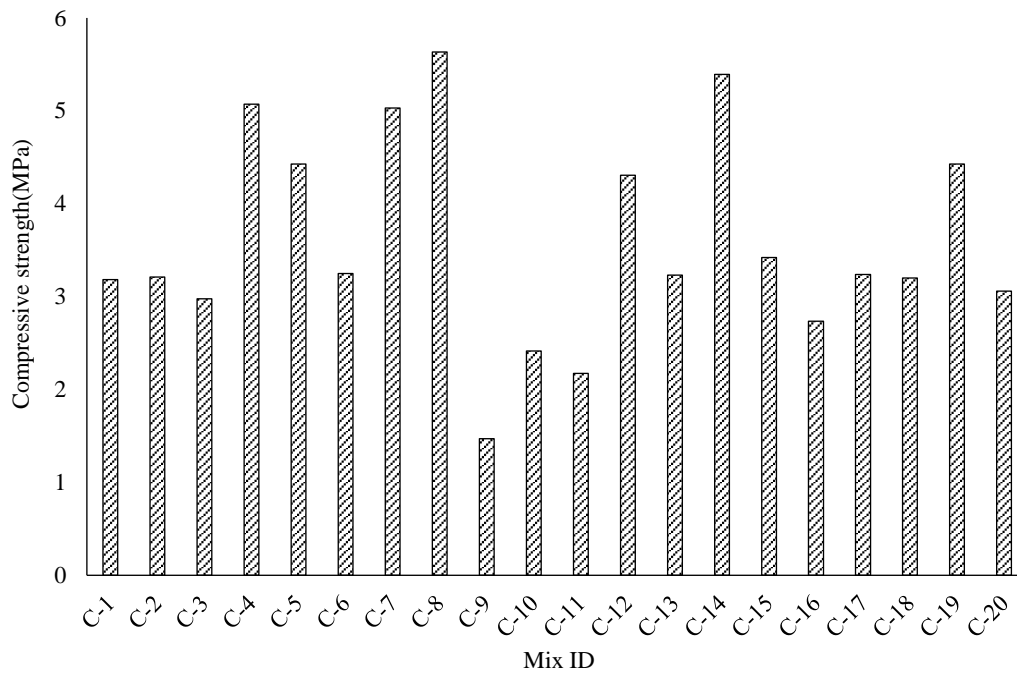
### Compressive Strength After Temperature Curing

The samples were placed into an oven after 28 days; the curing temperature was 200 °C for 24 hours. The samples were taken out of the oven in order to allow them to cool down at room temperature; after that, the sample was placed in a compressive strength testing machine, and then the load was applied consistently and continuously. Figure 9 shows the recorded value of Compressive strength after temperature curing for all mixes. The highest compressive strength recorded was on mix C-8. This is due to the rate at which aluminosilicates materials (fly ash and bentonite) were dissolved in the presence of alkaline activators increases at elevated temperatures. In general, increased temperature speeds up the polycondensation processes between dissolved silica and alumina species. In this mix, an equal percentage of fly ash and bentonite was used.

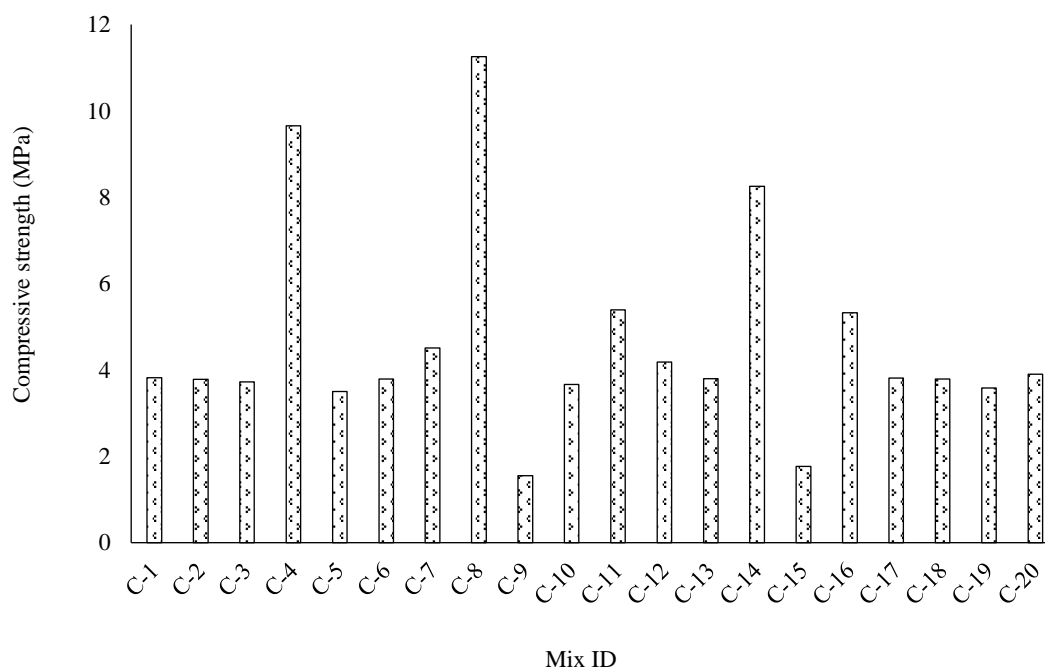
### Water Absorption

Figure 10 shows the water absorption for all mixes. After the samples were cured in water for 24 hours, their weight was recorded. Subsequently, the samples were placed in an oven at 200 degrees Celsius for 24 hours, during which time their dry weight (M1) was calculated—the weight sample following a 24-hour curing period in water (M2). The formula used to compute the percentage of water

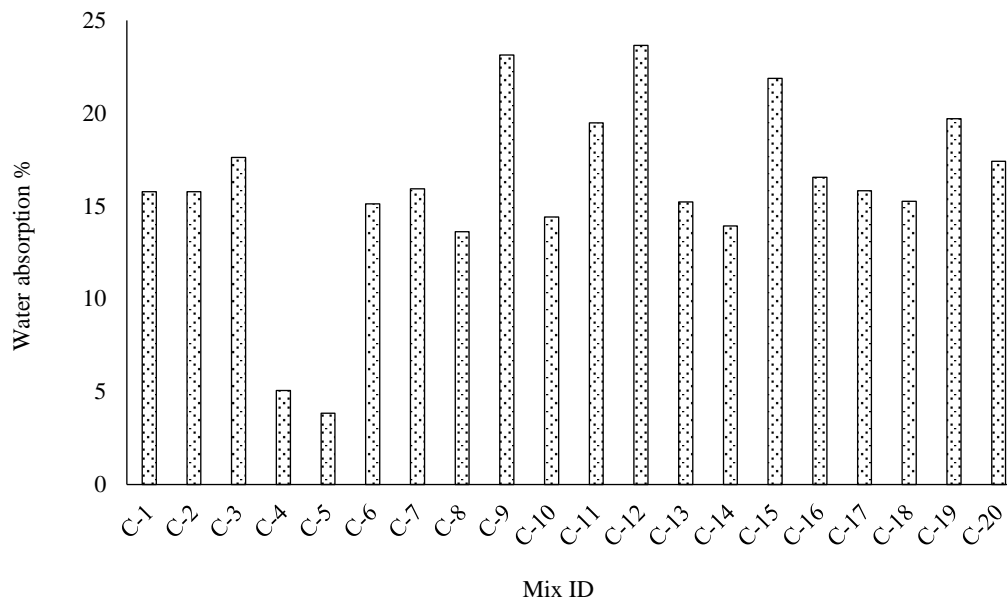
absorption was  $(M2-M1/M1 * 100)$ . The highest recorded water absorption percentage was on mix C-12. This is because the fly ash particles contain a large amount of unburned carbon and are not completely reactive, which results in a more porous structure. On the other hand, bentonite swells easily; it absorbs large volumes of water, increasing the initial water content of the materials and end porosity. The concentration of the alkali activator has an impact on the polymerization process. An excessive concentration has caused efflorescence and micro cracking, which increased the absorption of water in that mix.



**Figure 8.** Compressive strength at 28 days.



**Figure 9.** Compressive strength after temperature curing for mixes.



**Figure 10.** Water absorption for all mixes.

### RSM Modelling and Optimization

#### RSM analysis

The experiments were carried out for all mix proportions according to Table 4 of mix matrix design, and the results are shown in Table 6; in this table, F:1, F:2 and F:3 represent Oxide Ratio, Alkali Activated Ratio and Molarity, respectively. While R:1, R:2, R:3, R:4, R:5 and R:6 represent the responses flow table, fresh density, compressive strength after 28 days, Compressive strength after temperature curing, Density after water curing and Water absorption, respectively.

**Table 6.** Mix design matrix and responses.

MIX ID	F:1	F:2	F:3	R:1	R:2	R:3	R:4	R:5	R:6
C-1	3.715	2.3	12	117	1966.31	3.184	3.821	1979.32	15.77
C-2	3.715	2.3	12	119	1968.31	3.21	3.78	1982.23	15.77
C-3	3.715	2	12	115	1906.38	2.977	3.725	1954.23	17.62
C-4	2.74	2	16	110	2011.97	5.07	9.657	2025.35	5.07
C-5	2.74	2.6	16	140	1889.26	4.426	3.5	1998.32	3.84
C-6	3.715	2.3	12	118	1972.31	3.25	3.79	1986.87	15.11
C-7	3.715	2.6	12	120	1823.62	5.029	4.506	1989.26	15.93
C-8	2.74	2	8	111	1772.25	5.633	11.253	1825.85	13.62
C-9	4.69	2.6	16	128	1746.56	1.47	1.552	1829.76	23.13
C-10	4.69	2	8	109	1820.76	2.414	3.661	1832.85	14.41
C-11	4.69	2	16	114	1889.26	2.172	5.392	1902.58	19.48
C-12	2.74	2.6	8	136	1800.79	4.305	4.184	1935.03	23.65
C-13	3.715	2.3	12	121	1973.31	3.23	3.8	1978.54	15.23
C-14	2.74	2.3	12	118	1894.96	5.392	8.25	1917.77	13.92
C-15	4.69	2.6	8	122	1775.10	3.42	1.77	1843.59	21.88
C-16	4.69	2.3	12	119	1892.11	2.736	5.325	1912.19	16.55
C-17	3.715	2.3	12	120	1974.31	3.24	3.81	1976.23	15.83
C-18	3.715	2.3	12	118	1969.31	3.2	3.79	1982.25	15.25
C-19	3.715	2.3	8	119	1797.93	4.426	3.581	1820.72	19.71
C-20	3.715	2.3	16	125	1889.26	3.058	3.903	1903.48	17.41

**Flow table**

Figure 11 shows a surface diagram of the flow table as well as different flow table intervals for a variety of variables. Equation 1, a quadratic formula where "A" stands for oxide ratio, "B" for alkali-activated ratio, and "C" for molarity, was used to estimate the values of flow table tests.

$$\text{Flow table} = +119.95 - 2.3 A + 8.7 B + 2 C - 3.5 AB + 1 AC + 0.75BC \quad \text{Eq.1}$$

**Fresh density**

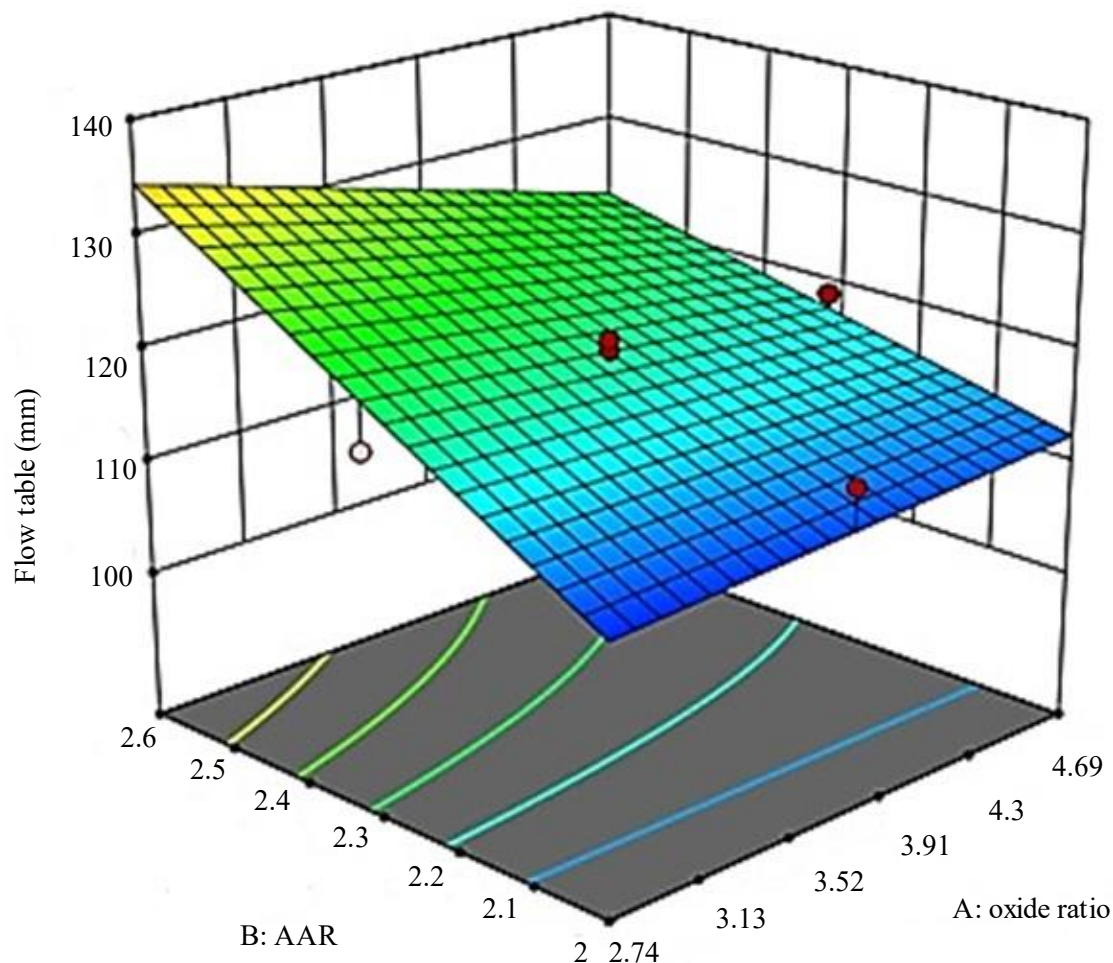
A variety of factors are shown for different fresh density of mortar intervals in Figure 12. The following quadratic equation, Eq. 2, was used to determine the fresh density of mortar. The response surface methodology was used to generate this equation in accordance with the mix matrix design.

$$\text{Fresh density} = +1944.83 - 24.54A - 36.52B + 45.94C - 11.77AB - 36.02AC - 31.03BC - 12.59A^2 - 41.13 B^2 - 62.53 C^2 \quad \text{Eq. 2}$$

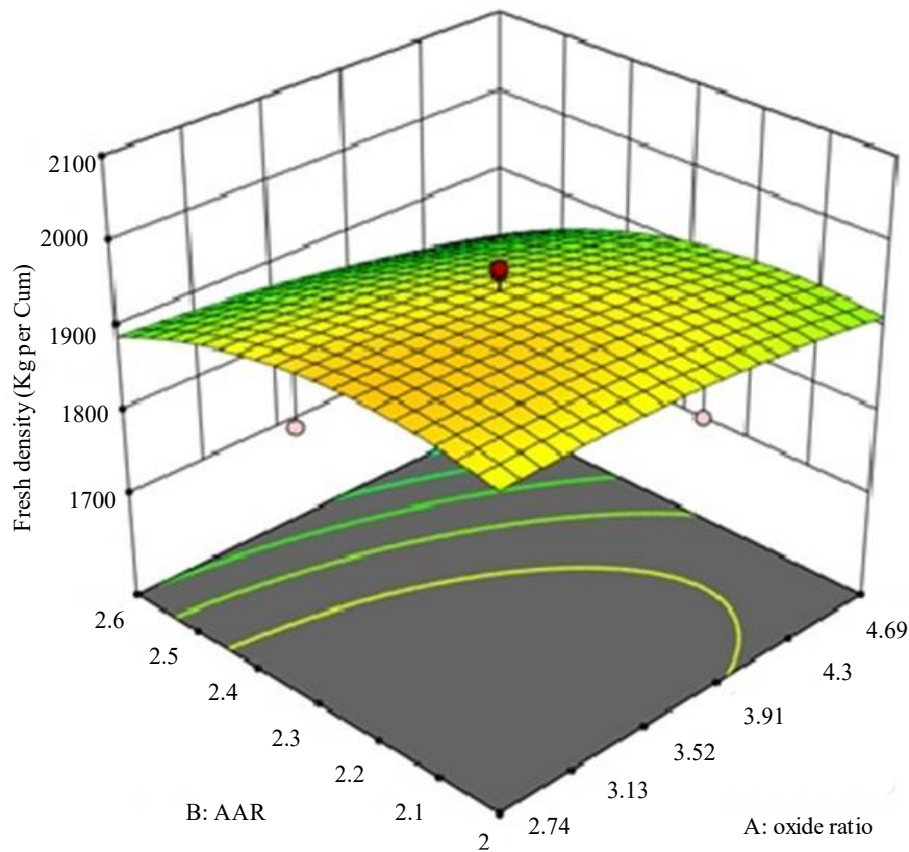
**Compressive strength after 28 days**

Compressive strength can be computed using RSM analysis by taking into account the following quadratic equation, Eq. 3. Based on the mix matrix design, response surface methodology generated that equation. Figure 13 illustrates how compressive strength was varied.

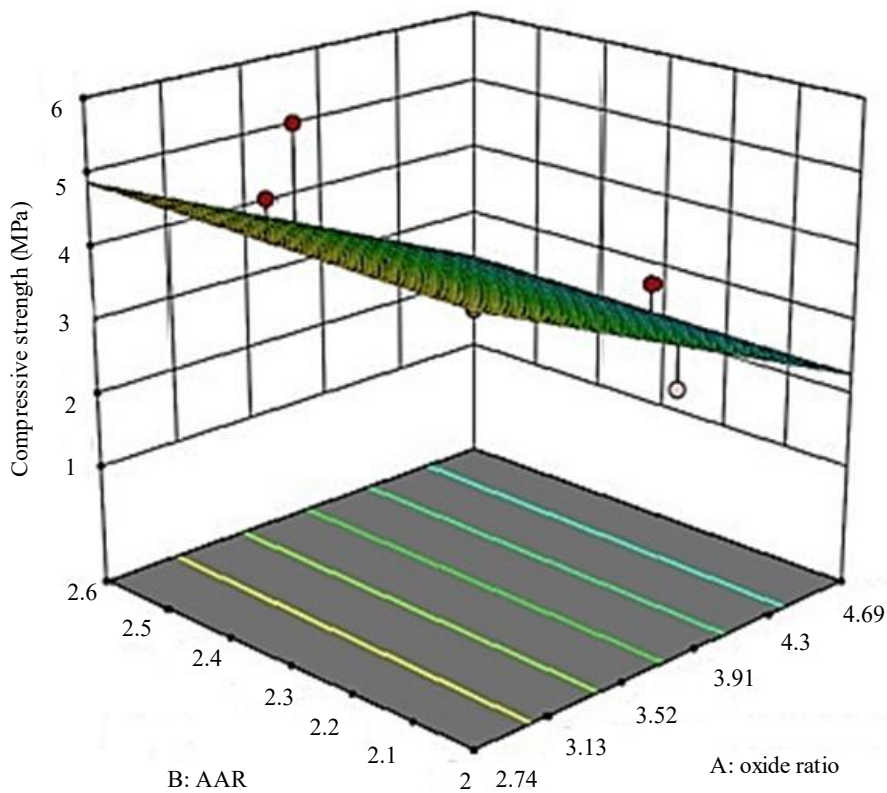
$$\text{Compressive strength} = +3.59 - 1.26A + 0.03B - 0.4C \quad \text{Eq. 3}$$



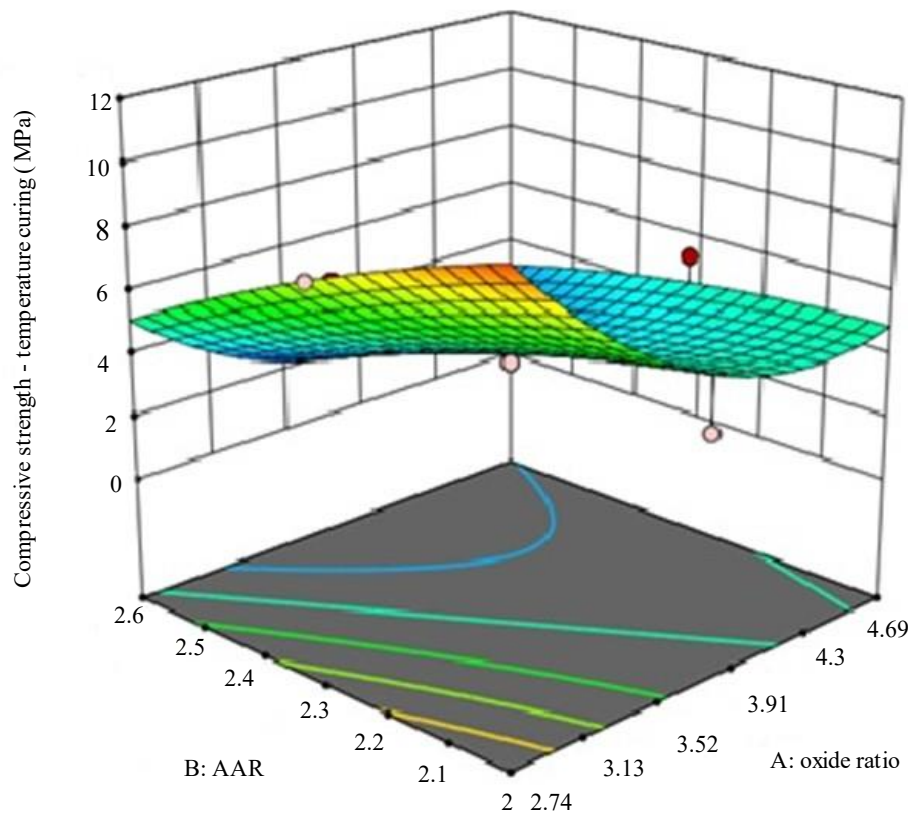
**Figure 11.** 3D surface diagram for representing flow Table.



**Figure 12.** 3D surface diagram for representing the fresh density.



**Figure 13.** 3D surface diagram for representing compressive strength.



**Figure 14.** 3D surface diagram for representing compressive strength - temperature curing.

#### ***Compressive strength after temperature curing***

By considering the following quadratic equation, Eq. 4, compressive strength after temperature curing may be calculated using RSM analysis. The response surface methodology produced this equation based on the mix matrix design. Figure 14 shows the variation in compressive strength after temperature curing.

$$\text{Compressive strength - Temperature curing} = +4.07 - 1.91A - 1.81B - 0.04C + 0.93AB + 0.47AC - 0.12BC + 2.28A^2 - 0.38B^2 - 0.75C^2 \quad \text{Eq. 4}$$

#### ***Density after water curing***

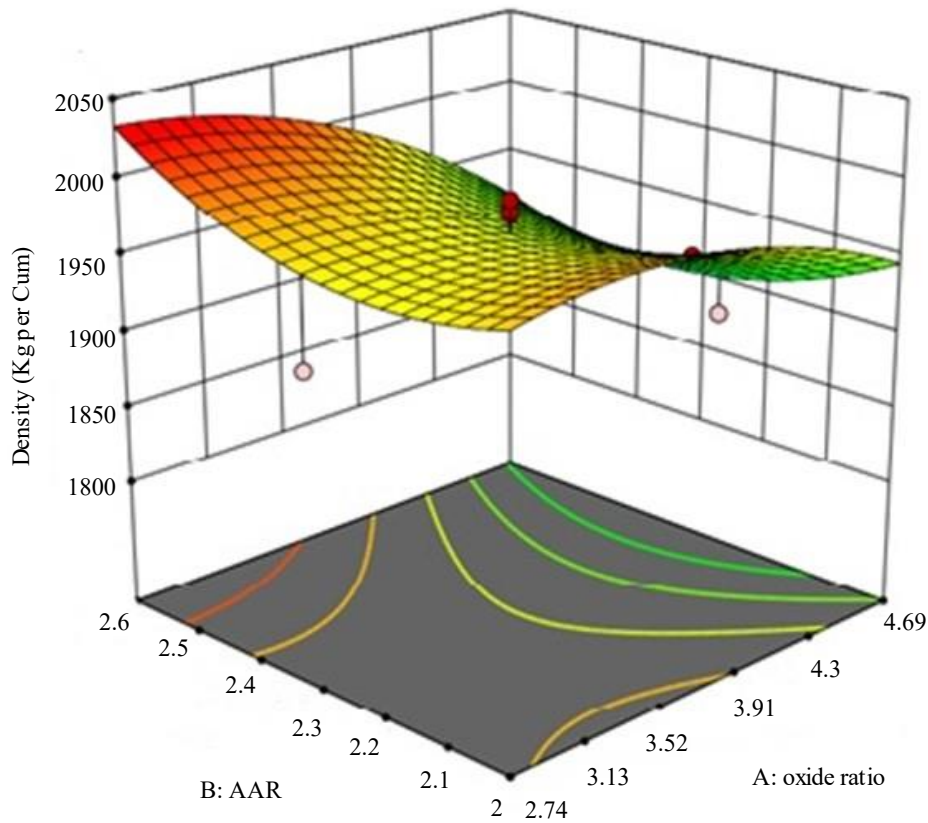
Equation 5 is a quadratic equation that can be used to identify density after water curing. The response surface methodology, based on the mix matrix design, has been used to produce that equation. Density after water curing values are displayed in Figure 15, where we can see how the values vary with the corresponding mixes and variables.

$$\text{Density} = 1964.59 - 38.13A + 5.51B + 40.14C - 18.02AB - 25.86AC - 27.47BC - 25.14A^2 + 31.62B^2 - 78.02C^2 \quad \text{Eq. 5}$$

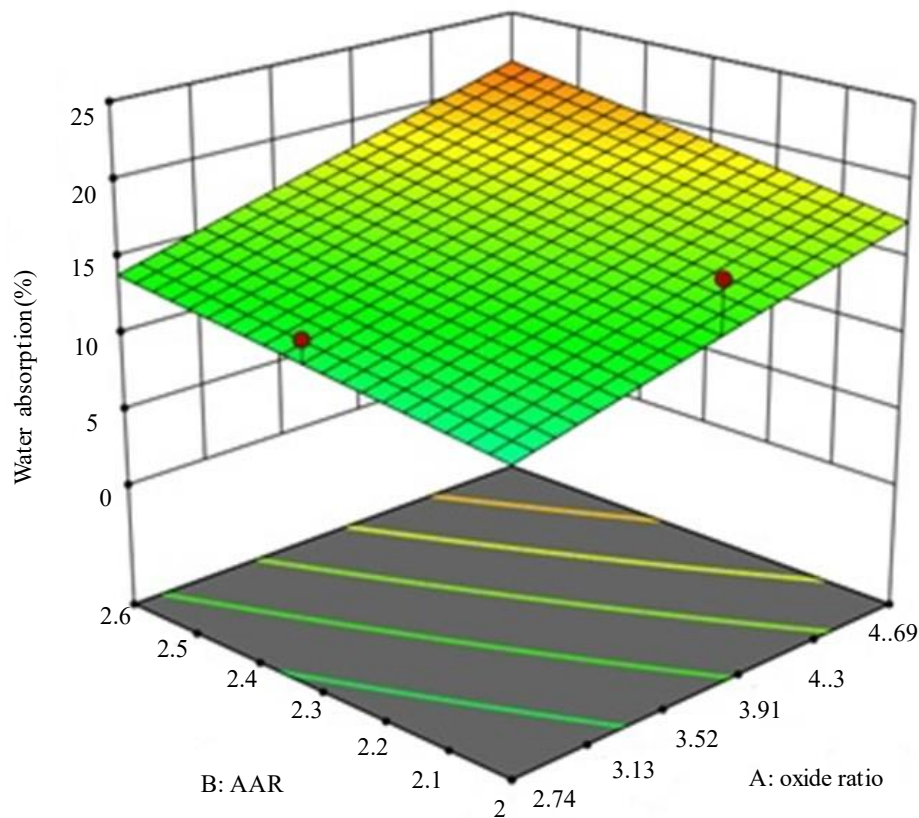
#### ***Water absorption***

Water absorption of geopolymer mortar can be determined using equation 6, a quadratic equation. This quadratic equation comes from the response surface methodology, which was based on the mixed matrix design. Values for water absorption are shown in Figure 16, where we can observe how the values change in relation to the relevant mixes and variables.

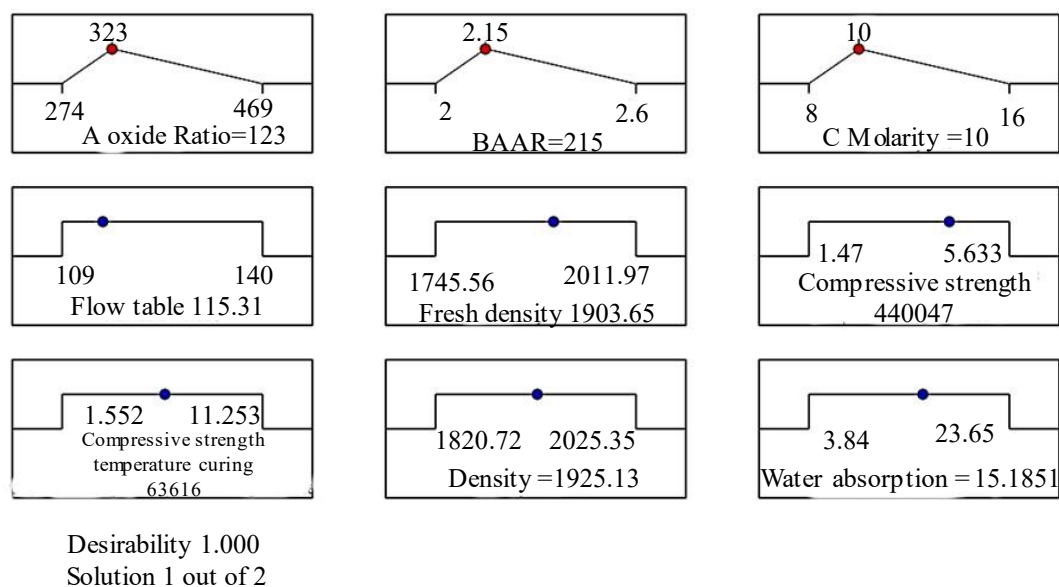
$$\text{Water absorption} = +15.959 + 3.535A + 1.823B - 2.434C + 0.29AB + 4.335AC - 1.885BC \quad \text{Eq. 6}$$



**Figure 15.** 3D surface diagram for representing density.



**Figure 16.** 3D surface diagram for representing water absorption.



**Figure 17.** Optimization ramp diagram.

### Optimization

We used the response surface methodology for optimization. The goal of the optimization procedure is to identify the set of parameters that yields the lowest water absorption and the highest compressive strength. By using this optimization technique, a geopolymer mortar composition that satisfies particular performance standards has been created. This paper investigates the Response Surface Methodology (RSM) optimization of alkali-activated geopolymer mortar characteristics. The mechanical strength and durability of the geopolymer mortar are examined in relation to important parameters, including Oxide Ratio, Alkali Activated Ratio (sodium silicate and sodium hydroxide proportions) and molarity of sodium hydroxide. A methodical technique for designing tests, analyzing data, and figuring out the best mix of variables to achieve desired attributes was offered by RSM. The findings of this study will help create high-performing, environmentally friendly geopolymer mortars for a range of construction uses. Statistical software was used to analyze the experimental data from this study in order to create a response surface model. The model describes the link between the input parameters and the output responses. This model can be used to determine the best combination of factors to achieve desired attributes as well as to forecast response values for various combinations of components.

The analytical results indicated that the fly ash content concentration had a substantial impact on the compressive strength of the geopolymer mortar. In general, compressive strength increased with increasing fly ash content. It was discovered that each of the variables had an impact on water absorption on the geopolymer mortar. Lower water absorption was typically the outcome of increasing the sodium hydroxide content (molarity), predicting greater durability. With ideal ranges for each component, the fly ash content and sodium silicate concentration had a greater impact on water absorption. This study effectively illustrated how RSM may be used to optimize the composition of geopolymer cement block that has been alkali-activated. The findings demonstrated that the ratios of fly ash, bentonite, sodium silicate, and sodium hydroxide had a substantial impact on the compressive strength and water absorption of the geopolymer block. The best set of parameters for obtaining the desired qualities was found through the optimization procedure. Figure 17 shows the optimization Ramp diagram.

### CONCLUSION

This research project was based on an alkali-activated geopolymer binder, in which bentonite and fly ash have shown good mechanical properties and are environmentally friendly, making it a viable material for use in sustainable buildings.

- Geopolymer mortar composed of bentonite and fly ash supports sustainable building methods. By encouraging the recycling of industrial waste materials and lessening the carbon footprint associated with the traditional manufacture of Portland cement.
- The consistency and workability of geopolymer mortar increased due to higher molarity and higher alkali-activated ratio
- The highest molarity of NaOH and the lowest alkali-activated ratio lead to the higher density of geopolymer mortar.
- Bentonite is less reactive than fly ash, which resulted in a decrease in compressive strength at an early age. But when properly activated, bentonite increases strength by supplying more aluminosilicates for the creation of geopolymers.
- Fly ash increases the early compressive strength of geopolymer mortar. A dense, homogenous matrix is formed with the help of fly ash.
- Temperature curing speeds up the geopolymerization process and improves the intermolecular interactions of the aluminosilicates source materials. Which results in increasing the resistance to heat stress.
- The highest water absorption is the result of fly ash particles, which have a more porous structure because high content of unburned carbon and partial reactivity.
- The best optimal values that can be utilized in the mortar mix are 12 molarity and 2.3 alkali-activated ratio.
- The highest compressive strength was observed with the use of a 2.74 oxide ratio, 2 Alkali Activated ratio, and eight molarity.
- Response surface methodology has been used to determine the relationship between input variables and output responses and to assess whether factors have a significant impact on response.

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