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Geopolymer Concrete Production by Using Nano-Bauxite Binder

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ABSTRACT

Iraqi bauxite ore was used in the manufacturing of geopolymer mortar and concrete. To de-hydroxylate and turn bauxite into an amorphous phase, it was heated to 650 degrees Celsius. Mixing bauxite nanoparticles with an active alkaline solution produces a geopolymer of high grade due to their high efficiency. The nano-bauxite geopolymer mortar is produced following ASTM C109 with various quantities of alkaline solution with molarity (8, 10, 12, and 14). At 3, 7, and 28 days, the maximum compressive strength of mortar with a molarity of 12 was 20.2, 49.7, and 65.3 MPa, respectively. The same quantity of molarity for the mortar was utilized for the production of geopolymer concrete using an alkaline solution. The weight of nano bauxite was substituted for the percentage of nano-glass and carbon nano-tubes that were included in the geopolymer concrete. This resulted in the utilization of nano-glass and carbon nano-tubes, the best ratios are 8% silica merge with 0.01% of carbon nano-tubes. At the age of 28 days, the water absorbency value was found to be 1.78%, and it was noted that the increased compressive strength reached 81.4 MPa. For the polymerization and performance hardening of samples at low temperatures (20±3 °C), geopolymers with nano-bauxite binders were manufactured without heat treatment. The increased compressive strength as well as resistance to freezing and thawing tests are a result of the superior performance and high requirements of nano-materials. XRD examination was performed, many geopolymer phases were generated, and the bond structures between alumina and silica were observed; these results confirm the development of geopolymer.

Keywords: Binder Nano-Bauxite, ball mill, alkaline solution, compression strength, and absorption.

INTRODUCTION

Geopolymers are aluminosilicate bond-based inorganic, amorphous or semicrystalline materials. Their production by polymerization process requires a high content of aluminium and silica, such as fly and volcanic ashes, metakaolin, slag blast furnaces or any other aluminosilicate sources [1, 2]. Therefore, bauxite is suitable for manufacturing geopolymers, because it includes large concentrations of hydrated alumina and silica impurities [3]. According to common knowledge, geopolymer binders may replace typical cement binders in the concrete industry and reduce CO_2 emissions by 78%. The likelihood of global warming increases as a result [4]. Thus, geopolymers can be characterized as industrial minerals that are produced in an industrial context; their most desirable qualities are high durability, softness, and hardness [1, 2]. Years ago, Davidovits introduced the sialate term; this name refers to the structures of aluminosilicate, the connections Si–O–Al described as sialate bonds, but the Si–O–Si connections named as siloxo bonds, from the classification of Davidovits, it was possible to obtain a method to defined the geopolymers composition based on their silica-alumina ratio [5, 6]. On the basis of the above, Geopolymers can be divided into types such as: (–Si–O–Al–O–) sialate or polysialate; (–Si–O–Al–O–Si–O–) sialate-siloxo or polysialate-siloxo and (–Si–O–Al–O–Si–O–Si–O–) sialate-disiloxo or polysialatedisiloxo, represented in Figure 1. In civil engineering applications, a low Si: Al ratio is very suitable [7]. It is achieved by using bauxite source material. The requirement for heat treatment to solidify geopolymer concrete is one of the known drawbacks of this material. Accordingly, nanotechnology was employed in this study, and nano-bauxite was used as a binder to provide very high-quality results, which required no heat treatment and possessed a high compressive strength.

GEOPOLYMERS

Previous research has predominantly classified geopolymers as inorganic polymers. In addition, the formation of (Si–O–Al) bonds occurs in a three-dimensional semicrystalline to amorphous material resulting from the reaction of an aluminum silicate source with an alkaline solution (often sodium hydroxide or KOH) [8, 9]. Geopolymers are dependent on the chemical interaction that takes place between alkaline liquid and silico-aluminate components [10]. In recent years, there has been a proliferation of research published in academic journals that presents findings that are in direct opposition to one another about geopolymers. in particular on the criteria that influence their qualities, as well as on their microstructure, selected precursor, environmental effect, durability, and mix-design approaches. This literature will seek to provide an overview of some of the fundamental principles for comprehending geopolymer research, as there has been more public work done on the most recent developments in geopolymer science. In addition to the difficulties associated with the procurement of raw materials, which restrict the production of this material at a large scale. The objective of this study and the purpose of this work was to produce a high-efficiency geopolymer by making use of a novel source material; specifically, Iraqi nano-bauxite, to obtain a geopolymer paste that is compatible with civil engineering projects. Rigidity in a three-dimensional network can be initiated by using a low ratio of silica to aluminas, such as 1, 2, or 3. Bauxite can produce the low silica-to-alumina ratio that is necessary for a variety of civil engineering applications, hence it is an advantage of using bauxite [11].

MATERIALS

Iraq Nano-Bauxite (NBa)

It is necessary to define the term bauxite in this context. It can be defined as a mixture of minerals consisting of a mineral ore containing aluminum oxide and one or more water molecules, together with contaminants such as phosphorus (Na_2O, MgO, CaO, TiO_2, $Fe2O_3$, K_2O, and SiO_2). Gypsum, dyspor, and boehmite are the three minerals that make up hydrated aluminum oxide. To convert bauxite to a random phase and complete the dehydroxylation process, bauxite is heated to 650 degrees Celsius [12]. The bauxite from Iraq was used for the mining operation in the Western Desert, which is located in the Rutba-al Anbar province [13, 14]. The XRF analysis results for the chemical components of Iraqi bauxite are presented in Table 1. To obtain nano-bauxite, the crushing process is followed by the milling process, which is performed by a ball mill. The crusher device is used to reduce large blocks into smaller ones after the crushing process, as depicted in Figure 2. It is a source of alumina, and when combined with a sodium silicate solution, the result is the formation of a geopolymer. Figure 3 shows the results of an XRD analysis of bauxite, and Figure 4 depicts an FE-SEM analysis of nano-sized bauxite.

Nano glass (NG)

Glass trash, often known as window glass, is a source of silica because it has a high amount

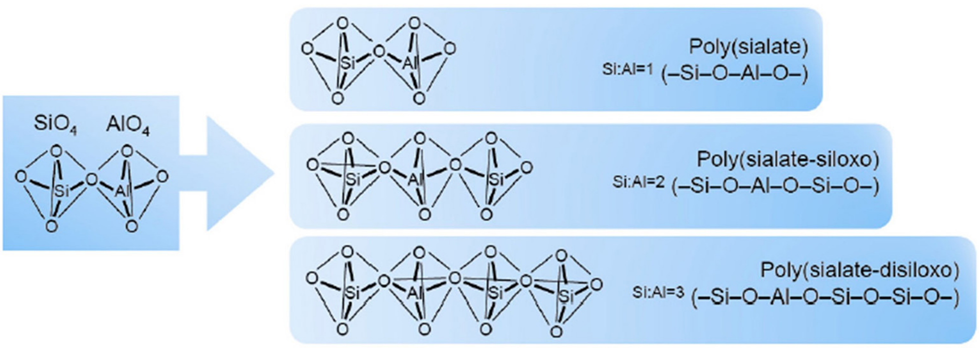

Fig. 1. Type of geopolymers according to the Davidovits model

Fig. 2. Crusher and ceramic ball mill device

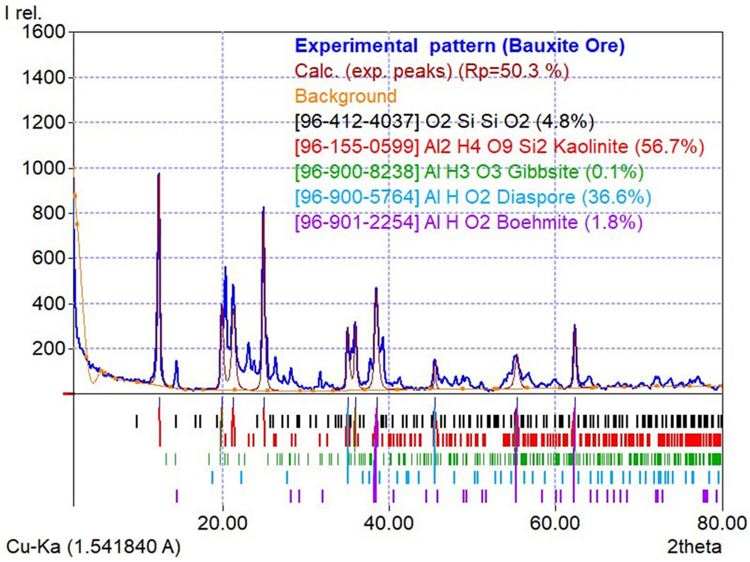

Fig. 3. XRD test of nano-Iraqi bauxite

of amorphous silica in its composition. Table 2 presents the results of an XRF investigation of the chemical composition of glass. Before grinding, it is vitally important to thoroughly clean the glass waste to prevent any undesirable chemical or physical interactions with contaminants. The glass is ground to the nanoscale, which highlights the significance of nano-silica in the process of enhancing the characteristics of geopolymers [15]. Figure 5 shows the results of an XRD analysis of nano-glass, Figure 6 depicts the results of the FE-SEM examination of nano-glass.

Carbon nano-tubes

A particular sort of carbon nanotube known as a multi-walled CNT was utilized in this study [16]. Because of its great tensile strength as well as its superior chemical and physical stability, it is ideally suited for usage in geopolymer mixes. The graphene sheets that make up the cylinder-like structure, which was manufactured in the United States, have an overall purity of more than 95%, a length of CNT that can reach up to 60 micrometers, and an outer diameter that can reach 58 nanometers. The XRD and FE-SEM tests that were performed on the CNT to diagnose its properties are depicted in (Figures 7 and 8) accordingly. According to the XRD analysis, the crystal structure of CNT has a hexagonal axis (trigonal system).

Alkaline solution

Alkaline solution and sodium silicate differ in several significant ways. The type of alkaline solution has a crucial impact on the polymerization procedure. Combining sodium hydroxide with sodium silicate solutions yields an alkaline solution. This accelerated the reaction between the source material and solution [17, 18]. According to [19, 20], the chemical composition of local (Industrial) type sodium silicate is Na_2O = 12.6%, SiO_2 = 34.4%, the specific gravity is 1.54, and the ratio of SiO_2: Na_2O is 2.7. Thus, water can be lowered by increasing silica concentration by evaporation. The sodium hydroxide utilized in this investigation was manufactured in Iran with a purity of 98. It is dissolved in distilled water to prevent the influence of unidentified pollutants on the formation of solutions with varying molarities (8M-10M-12M-14M). The needed molarity of sodium hydroxide solution and liquid sodium silicate were combined and stored at 23 ± 2°C for 24 h before usage.

Standard sand

In the testing of hydraulic cement mortars, standard sand, also known as silica sand, is typically used. Quartz is almost completely pure and consists entirely of grains that have their native shape preserved. In the course of this research, geopolymer bauxite mortar has been put through its paces using ordinary sand. In addition, the standard sand grading is done following ASTM C778, and it has a silica content of 92%. Table 3 displays the chemical composition of the sand.

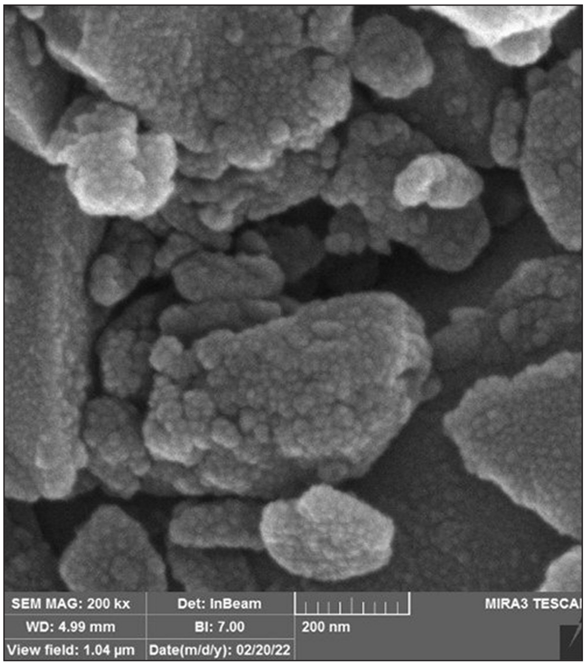

Fig. 4. FE-SEM image of Iraqi nano bauxite

Fine aggregate

The maximum size of natural fine aggregate has a particle size that is less than 4.75 millimeters, and it has a fineness modulus of 2.0. In addition, the specific gravity of natural sand is 2.6, the absorption of water percentage is 0.8, and the amount of sulphate is 0.08 percent by weight.

Coarse aggregate

Gravel that had been crushed and utilized as aggregate was acquired from the Badra quarry in the Wasit district of Iraq. This gravel was used as coarse aggregate in geopolymer concrete mixes. The largest size of the particles is 12.5 millimeters, the quantity of sulfate expressed as a percentage of SO3 is 0.017, and the absorption is 0.7%.

GEOPOLYMER BASED ON NANO-BAUXITE MIX DESIGN PREPARATION

Mortar mix design

In terms of mortar mix design, geopolymer mortar designs can be created using the same procedures as cement mortar. To create a nano-bauxite geopolymer mortar, nine experimental

Table 1. Chemical analysis (XRF) of Iraqi bauxite

Analyses	Al_2O_3	SiO_2	SO_3	Cl	K_2O	TiO_2	MnO	Fe_2O_3	CuO
Result	61.561	36.718	0.144	0.313	0.493	1.124	0.006	1.085	0.005

Note: *Chemical tests were conducted by done in National Center for Construction Laboratories \ Baghdad Central Laboratory.

Table 2. Chemical analysis (XRF) of glass waste*

Analyses	SiO_2	Al_2O_3	K_2O	Fe_2O_3	CaO	TiO_2	ZrO_2	Cl	SO_3
Result	85.078	4.654	1.250	0.358	7.997	0.061	1.011	0.202	0.293

Note: *Chemical tests were conducted by done in National Center for Construction Laboratories \ Baghdad Central Laboratory.

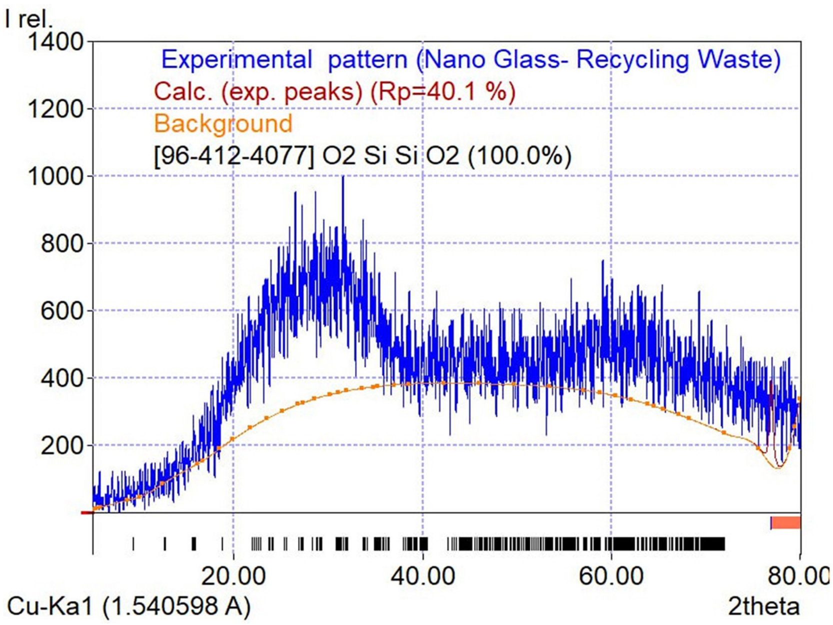

Fig. 5. XRD test of nano-glass

combinations were created, each beginning with four molars of alkaline solution (M1-M2-M3-M4). The geopolymer that is used in mortar is a combination of a regular sand, nano-bauxite, and an alkali solution in a predetermined ratio. In the course of this study, the optimal molarity, which was determined to be 12, was used for all of the other mixes. As it can be shown in Table 4, the performance characteristics of mortar have been enhanced by the utilization of nano-additives, specifically nano-glass and carbon nanotube. This study was carried out following the ASTM C109/C109M 16a specification. Samples of mortar are formed in a cube-shaped mold that has dimensions of 50 mm^3 across all three dimensions.

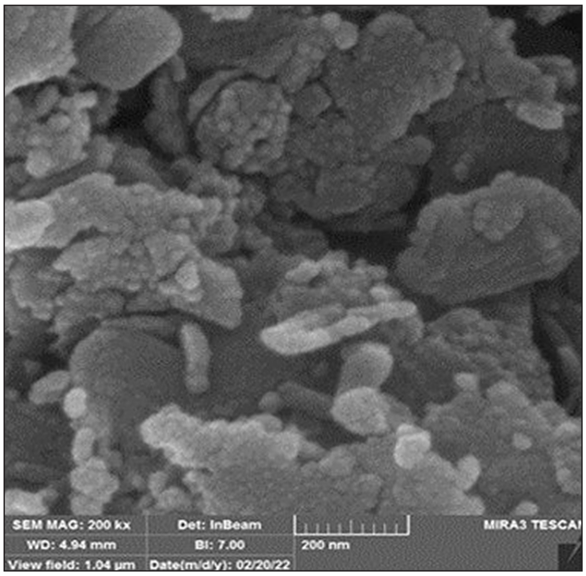

Fig. 6. FE-SEM image of Iraqi nano-glass

Concrete mix design

The procedure for preparing a geopolymer concrete mixture is laid out in detail in Table 5, as it may be seen in its completeness. In addition to analyzing the outcomes of geopolymer mortars and selecting the appropriate proportions for various nano-additives, three experimental mixtures were created for use in the production of geopolymer concrete, including 8% nano-silica, 8% nano-silica with 0.01% carbon nanotube, and reference samples. This was done so that the results could be applied to the production of geopolymer concrete. The pan of the mixer machine has a capacity of 0.1 cubic meters, and it was utilized in the process of preparing and mixing the nano-bauxite-based geopolymer concrete. Using a speed blender, the carbon nanotubes are mixed in separately and with extreme caution, before being combined with the other components. First, the carbon nanotubes are combined with a certain quantity of nano-bauxite binder. After thoroughly combining all of the components, including the coarse and fine aggregates as well as the additional additives. The contents are pressed into cubes with dimensions of 100 mm^3 on each side.

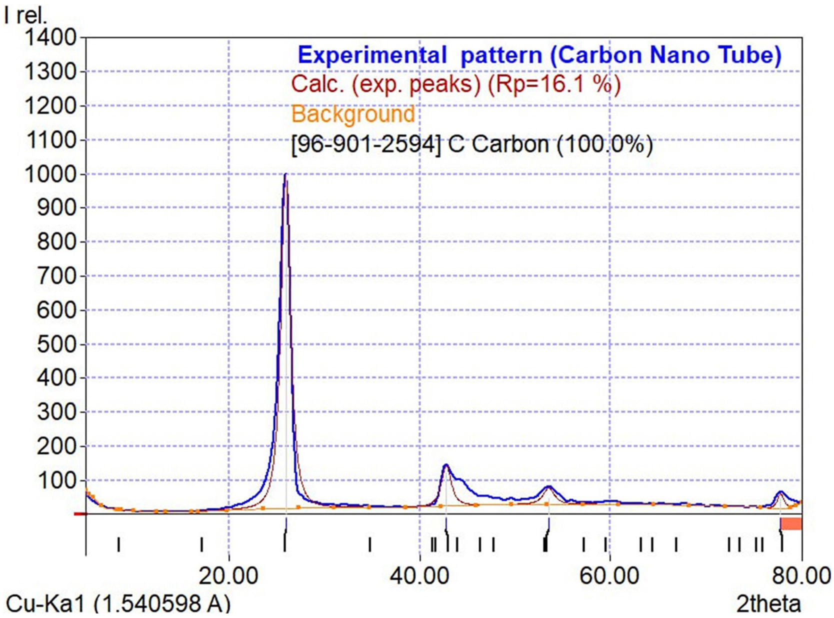

Fig. 7. XRD test of CNT

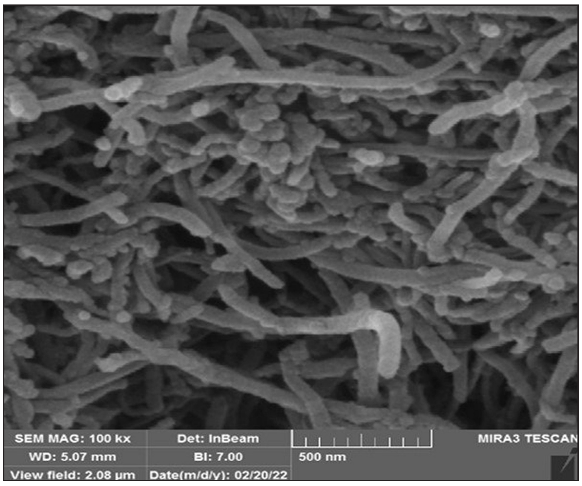

Fig. 8. FE-SEM image of CNT

Curing of geopolymer mortar & concrete

Without subjecting any of the samples to any kind of heat treatment, the hardening process is carried out mechanically at low temperatures across the board for both mortar and concrete. The samples were cast and stored in a separate room until they reached the minimum age for inspection, the temperatures in this room averaged between 20±3 °C. As a result, distinctive characteristics were recorded during the casting of the samples, and no evidence of heat treatment was found. During the process of opening the mold, there was apparent evidence of the material solidifying and taking the form of a coherent sample. This is because the binder nano-bauxite was made using nanotechnology, which led to a speed-up in the process of offering the greatest results.

TESTS RESULTS

XRD analysis of geopolymer-based nano-bauxite

To conduct the XRD analytical investigation, a sample of the nano-bauxite based on geopolymer served as the basis. It refers to the process in which many crystal systems of the geopolymer structure are formed (appearance Al-O-Si compound). Additionally, these crystal types describe the formation of geopolymers in various crystal systems, such as an orthorhombic system in the type of andalusite and triclinic (anorthic) in the Al_2O_5Si type. The monoclinic in the SiO_2 type as a result of the pre-existing silica; thus, this crystal system

Table 3. Chemical analysis (XRF) of standard sand*

Analyses	SiO_2	Al_2O_3	Nd_2O_3	K_2O	Eu_2O_3	CaO	SO_3	Fe_2O_3	TiO_2
Result	92.026	5. 907	0.753	0.456	0.266	0.206	0.128	0.125	0.061

Note: *Chemical tests were conducted by done in National Center for Construction Laboratories \ Baghdad.

Table 4. Compressive strength of mixing ratios of geopolymer mortar according to cement specification ASTM C109/C109M – 16a

Mix. No. & Mix ID	740 gm of base material (nano bauxite + nano additives) for 9 specimen's [50-mm] cubes [The nano additives are replaced by the weight of the nano-bauxite]						Sd*	Alkaline solution = 0.81 by wt. of base material in gm [Na_2SiO_3-to-NaOH ratio (by weight)] = 2.5	
	Nano bauxite		Nano glass		CNT			Molarity & wt. of NaOH solution in gm	Na_2SiO_3 solution in gm
	%	gm	%	gm	%	gm			
Mix 1 (Nano bauxite)	100	740	---	---	---	---	2035	8M (171.2)	428.2
Mix 2 (Nano bauxite)	100	740	---	---	---	---	2035	10M (171.2)	428.2
Mix 3 (Nano bauxite)	100	740	---	---	---	---	2035	12M (171.2)	428.2
Mix 4 (Nano bauxite)	100	740	---	---	---	---	2035	14M (171.2)	428.2
Best values for mortar compressive strength at 12 molarity, so it was approved for use with other nano additives									
Mix 5 (Nano bauxite+ Nano glass)	96	710.4	4	29.6	---	---	2035	12M (171.2)	428.2
Mix 6 (Nano bauxite+ Nano glass)	92	680.8	8	59.2	---	---	2035	12M (171.2)	428.2
Mix 7 (Nano bauxite+ Nano glass)	88	651.2	12	88.8	---	---	2035	12M (171.2)	428.2
Mix 8 (Nano bauxite+ CNT)	100	740	---	---	0.01	0.074	2035	12M (171.2)	428.2
Mix 9 (Nano bauxite+ CNT)	100	740	---	---	0.02	0.148	2035	12M (171.2)	428.2

Note: * Standard sand according to specification ASTM C778(20-30)، using 2035 gm for 9 specimens [50-mm] Cube.

Table 5. Mixture's constituents of geopolymer concrete (kg/m^3)

Mix No.	Mix ID	Binder (kg)		Fine agg. (kg)	Coarse agg. (kg)	Molarity for NaOH solution **&** Alkaline solution by wt. of binder	CNT (kg)	Compressive strength (MPa)	
		Nano bauxite (kg)	NG (kg)					7 days	28 days
1	Reference-Bauxite 100%	400	–	640	1100	(12M) 0.8	–	43.7	63.9
2	Bauxite 92%+NG8%	368	32.0	640	1100	(12M) 0.8	–	46.3	74.9
3	Bauxite92%+NG8% + CNT0.01%	368	32.0	640	1100	(12M) 0.8	0.04	48.9	81.4

yields geopolymers with high durability and good compressive strength specifications, both of which are produced by the material. Figure 9 presents the results of the XRD investigation performed on the nano-bauxite based on geopolymer.

Compressive strength test

According to the cement specification (ASTM C109/C109M 16a), the results of the geopolymer mortar compressive strength are displayed in Figure 10. The cubes were measured using a hydraulic compression machine with a capacity of 300 kilonewtons, and their measurements are 50 millimeters on each side by 50 millimeters on each face. In addition, the examination was performed at the ages of 3 days, 7 days, and 28 days. The compressive strength of geopolymer concrete was determined using the same protocols as those used for regular concrete (BS. 1881: Part 116: 1989). The volume of a cube made of geopolymer concrete is 100 millimeters cubed on all sides. The compressive strength of geopolymer concrete was evaluated with the assistance of a hydraulic compression machine that had a capacity of 3000 KN. The evaluation was carried out at ages 7 and 28 days, as seen in Figure 11. The mechanical compressive strength of geopolymer concrete can be computed by utilizing the following formula: fc' = P/A, where: fc' represent compressive mechanical strength in (MPa), P is maximum load was applied in (N) and A represent the cross-sectional area of applied load in the specimen (mm^2).

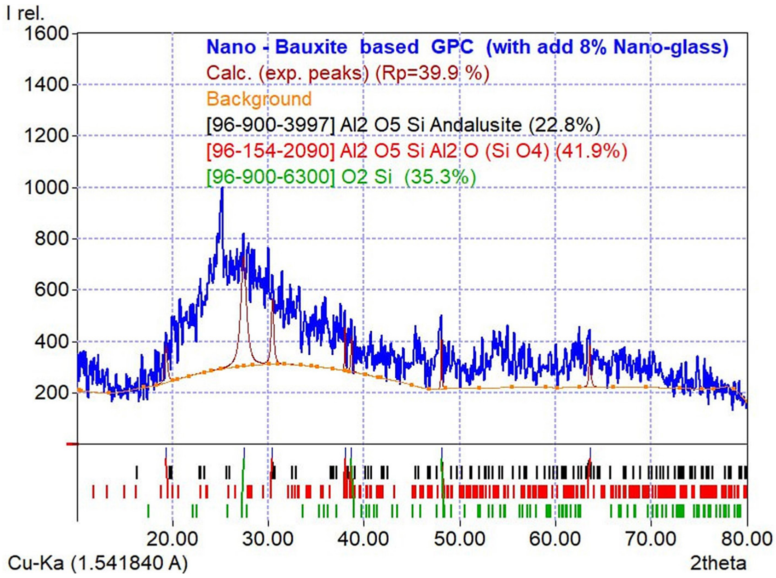

Fig. 9. XRD analysis of geopolymer chains formed

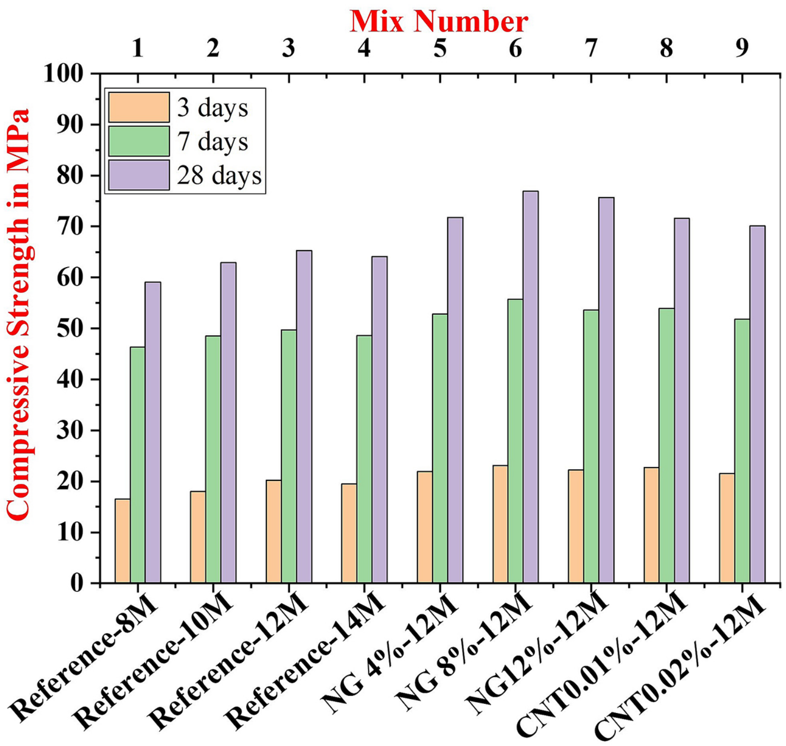

Fig. 10. Relationship of compressive strength with different geopolymer mortar mixes

Water absorption

For the aim of this study, the water absorption test of geopolymer concrete was carried out under the standard (ASTM C642- 13), making use of the identical proportions of the concrete mix design as shown in Table 5. Preparing specimens in the form of cubes with dimensions of 100 millimeters on each side to conduct an absorption test after 28 days (see Table 6). The percentage of silica (nano glass) affects the amount of water that can be absorbed by the material; this amount of water absorption reduces as the percentage of additional silica reaches 10%.

Freezing and thawing test

The freezing and thawing compressive strength test, often known as FTCs, is carried out

Table 6. Compressive strength and water absorption of geopolymer concrete

Mix No. of geopolymer concrete	Compressive strength of at 28 days	Water absorption (%)
Mix 1	63.9	1.859
Mix 2	74.9	1.784
Mix 3	81.4	1.783

Table 7. A Freezing and Thawing test

Geopolymer concrete mix no.	Freezing & thawing cycles no.	Compressive strength
Mix 1	0	63.9
Mix 2		74.9
Mix 3		81.4
Mix 1	100	63.8
Mix 2		74.9
Mix 3		81.3
Mix 1	200	61.4
Mix 2		72.7
Mix 3		80.1

per the methodology outlined in ASTM C666, with the specimens being in an exposed dry condition. After 28 days, the samples were delivered to the customs cabinet of FTCs. Samples of geopolymer concrete were prepared in four different groups, each with dimensions of 100 millimeters squared. As it can be seen in Table 7, the samples were subjected to both 100 and 200 cycles of being frozen and thawed.

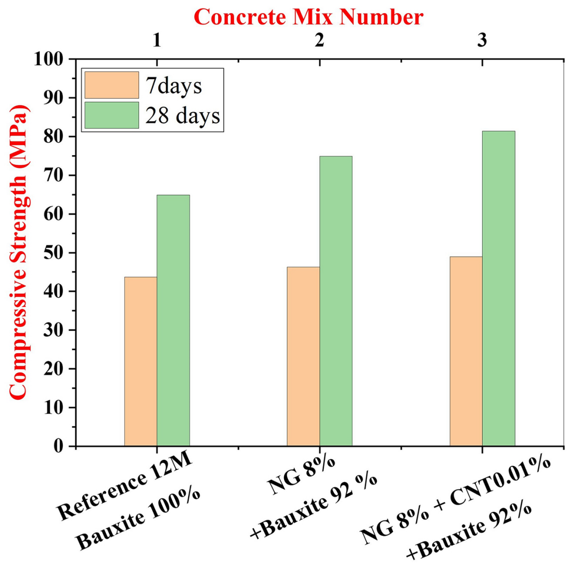

Fig. 11. Compressive strength of geopolymer concrete mixes

CONCLUSIONS

The following findings and inferences may be drawn after analyzing the results acquired during the examination. At various concentrations of alkaline solution, the compressive strength test of mortar revealed that all findings are exceptional. At a concentration of 12 molarity, the maximum mortar result was 20.2, 49.7 and 65.3 MPa at 3, 7 and 28 days respectively. The compressive strength of geopolymer concrete was determined to be 63.9 MPa after 28 days in a standard or reference mixture that was produced at a molarity of 12. The entire weight of nano-bauxite was substituted with varying amounts of addition, percentages of nano glass (4%, 8%, and 12%), and the addition of carbon nanotubes CNT at rates of 0.01% and 0.02%. When adding nano-glass at a rate of 8% and carbon nanotubes at a rate of 0.01%, the best and greatest value of compressive strength is achieved. In comparison to the figure used as a reference, the compressive strength in Mix3 has increased by approximately 27.4% as a percentage. It was shown that the addition of silica to geopolymer concrete had a substantial impact on the compressive strength after 7 days of age. This was noticed in geopolymer concrete, which is where the rate of hardening of geopolymer concrete is increased. The optimal water absorption rate of geopolymer concrete is 1.78%, which is influenced by the addition of silica to produce crack-free concrete. Up to 200 cycles of freezing and thawing indicate that the reference sample was not materially impacted. During XRD testing, it was noticed that several phases of geopolymers consisting of (Si-O-Al) linkages are generated. To obtain geopolymer concrete with superior characteristics, it is preferred to use fine and coarse aggregates that are free of contaminants and hazardous elements. To obtain strong cohesion and adhesion with its outside surfaces, the material should have a high silica content. Any molarity of the alkaline solution can be employed, and all findings will be positive. The use of plywood or PVC plastic in molds is important to prevent adhesion issues between steel molds and nanomaterials during casting. Hybridization between micro and nano-bauxite can be utilized with investigation and analysis of the outcomes.

REFERENCES

1. Davidovits, J. Geopolymers: Ceramic-like inorganic polymers. J. Ceram. Sci. Technol 2017, 8, 335–350.
2. Davidovits, J. Geopolymer Chemistry and Applications. 5-th edition. J. Davidovits. Saint-Quentin, France (Issue January 2008) 2020.
3. Kloprogge, J.T.; Ruan, H.D.; Frost, R.L. Thermal decomposition of bauxite minerals: infrared emission spectroscopy of gibbsite, boehmite and diaspore. Journal of Materials Science 2002, 37, 1121–1129.
4. Bakhtyar, B.; Kacemi, T.; Nawaz, M.A. A review on carbon emissions in Malaysian cement industry. International Journal of Energy Economics and Policy 2017, 7, 282–286.
5. Giacobello, F.; Ielo, I.; Belhamdi, H.; Plutino, M.R. Geopolymers and Functionalization Strategies for the Development of Sustainable Materials in Construction Industry and Cultural Heritage Applications: A Review. Materials 2022, 15, 1725.
6. Provis, J.L.; Van Deventer, J.S.J. Geopolymers: structures, processing, properties and industrial applications; Elsevier: 2009.
7. Abdullah, M.; Hussin, K.; Bnhussain, M.; Ismail, K.; Ibrahim, W. Mechanism and chemical reaction of fly ash geopolymer cement – a review. Int. J. Pure Appl. Sci. Technol 2011, 6, 35–44.
8. Davidovits, J. Geopolymers: man-made rock geosynthesis and the resulting development of very early high strength cement. Journal of Materials Education 1994, 16, 91–91.
9. Ding, Y.; Dai, J.-G.; Shi, C.-J. Mechanical properties of alkali-activated concrete: A state-of-the-art review. Construction and Building Materials 2016, 127, 68–79.
10. Davidovits, J. Geopolymer cement. A review. Geopolymer Institute, Technical Papers 2013, 21, 1–11.
11. Duxson, P.; Fernández-Jiménez, A.; Provis, J.L.; Lukey, G.C.; Palomo, A.; van Deventer, J.S. Geopolymer technology: the current state of the art. Journal of Materials Science 2007, 42, 2917–2933.
12. Davidovits, J. Chemistry of geopolymeric systems, terminology. In: Proceedings of Geopolymer; 9–39.
13. Phoo-ngernkham, T.; Chindaprasirt, P.; Sata, V.; Hanjitsuwan, S.; Hatanaka, S. The effect of adding nano-SiO_2 and nano-Al_2O_3 on properties of high calcium fly ash geopolymer cured at ambient temperature. Materials & Design 2014, 55, 58–65.
14. Riahi, S.; Nazari, A. The effects of nanoparticles on early age compressive strength of ash-based geopolymers. Elsevier: 2012.
15. Li, G. Properties of high-volume fly ash concrete incorporating nano-SiO_2. Cement and Concrete Research 2004, 34, 1043–1049.
16. Natsuki, T.; Endo, M. Stress simulation of carbon nanotubes in tension and compression. Carbon 2004, 42, 2147–2151.
17. Habert, G.; De Lacaillerie, J.D.E.; Roussel, N. An environmental evaluation of geopolymer based concrete production: reviewing current research trends. Journal of Cleaner Production 2011, 19, 1229–1238.
18. Rees, C.; Lukey, G.; Van Deventer, J. The role of solid silicates on the formation of geopolymers derived from coal ash. In: Proceedings of International Symposium of Research Students on Material Science and Engineering; 20–22.
19. Pacheco-Torgal, F.; Castro-Gomes, J.; Jalali, S. Alkali-activated binders: A review. Part 2. About materials and binders manufacture. Construction and Building Materials 2008, 22, 1315–1322.
20. Ng, C.; Alengaram, U.J.; Wong, L.S.; Mo, K.H.; Jumaat, M.Z.; Ramesh, S. A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. Construction and Building Materials 2018, 186, 550–576.