

Development of High Strength Geopolymer Concrete using Nano Silica



Nancy T. Hussien, Ahmed M. Ahmed, Mohamed H. Agamy, Gouda M. Ghanim

Abstract: Cement production became responsible of polluting the atmosphere by the emission of greenhouse gases. This issue motivate the researchers to work hard to develop a new cementitious materials used in concrete having much lower foot print in environmental pollution. This paper presents the development of high strength geopolymer concrete using nano silica. Ground granulated blast furnace slag (GGBFS) is used as main cementitious material and silica fume (SF) is used as cement replacement by different ratios. The alkaline activator is used in different temperature and samples cured by different methods. Nano silica then added to the optimum geopolymer concrete sample by ratios 1, 2 and 3% of the total weight of cementitious materials. Samples tested for mechanical properties. The results showed that using hot activator and oven curing samples gives higher mechanical properties. Also using nano silica up to 2% increases the compressive strength up to 24% at age 28 days.

Keywords: Hot activators temperature, normal activators temperature, oven curing and ambient temperature curing.

I. INTRODUCTION

Pollution in cement production is a major environmental issue throughout the world. Geopolymer concrete is an alternate cement as well as environment-friendly material in construction field [1]. Also, it has been reported that Global warming causes by the production of ordinary Portland cement through the emission of greenhouse gases looks carbon dioxide (CO₂) into the atmosphere contributes about 65% of the global warming. So cement production became responsible of this environmental issue. As a solution for this issue an alternative binder is used instead of portland cement. This solution is geopolymer concrete. Geopolymer concrete uses byproduct materials such as fly ash, silica fume, ground granulated blast furnace slag, rice husk and metakaolin as a binder [2]. GGBFS is one of these byproduct materials.

The main components of GGBFS are CaO (30-50)%, SiO₂ (28-38)%, Al₂O₃ (8-24)% and MgO (1-18)% according to American code [3]. Many researches had done either by partially or completely eliminating OPC and uses these byproduct materials instead of it. One of these researches is studying the development of high strength geopolymer concrete. A mixture of fly ash & ground granulated blast furnace slag (GGBFS) were used in geopolymer concrete and the results compared with conventional concrete. The results showed that the geopolymer concrete is more durable than conventional concrete [1]. Addition of alccofine "micro ground granulated blast furnace slag" as a replacement for geopolymer cement improves the mechanical properties [6]. Also it was reported that, specimens made by using a mixture of GGBFS & silica fume gives higher compressive strength than specimens made using GGBFS, silica fume & fly ash [7]. The optimum silica fume replacement percentage for obtaining maximum compressive strength in conventional concrete is up to 10% but after this ratio the compressive strength began to reduce [8]. Recently nano technology is being used or considered for use in many applications and it has received increasing attention in building materials. There is a limited knowledge about the mechanism by which NS affects the flow properties, setting times, consistency, workability, rheological, micro structural, mechanical properties etc. of cementitious mixes. A contribution to the development of building materials comprises adding synthetic silica to concrete and cement mortars, whereby the resulting product displays improved aging properties with regard to strength gain, sulphate attack and alkali silica reaction. Due to the high specific surface area for nano material sized colloidal nano silica (CNS) particles, they contribute a highly reactive siliceous material. However, it has not been established whether the more rapid hydration of cement in the presence of NS is due to its chemical reactivity upon dissolution (Pozzolanic activity) or to a considerable surface activity [9]. The addition of nano silica in the concrete mixture behaves not only as a filler to improve the microstructure, but also as an activator to promote pozzolanic reaction that resulting in the enhancement of the durability and mechanical properties of the mix [10,11]. Also, it has been reported that the maximum increase in strength was in 5% nano silica replacement. Workability of cement mortar decreased by increasing the amount of nano silica [12].

II. EXPERIMENTAL PROGRAM

With the objective of developing a technology to produce non-ordinary Portland cement concrete. The following principles were used:

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- Eliminating OPC completely and use geopolymer binder (GGBFS and SF) instead of it.
- Activatethe geopolymer cement with a combination of NaOH and Na₂SiO₃ with ratio 1:2.5.
- Use coarse aggregate of size 10mm and down.
- To improve the workability of fresh concrete Super plasticizer type "G" (sikament R2004)
- Nano silica added in different percentage to improve mechanical properties
- Samples cured in ambient temperature and in oven at temperature 75°C.

A. Material used

GGBFS used in this experimental work is water-cooled slag obtained from Ezz flat steel. Silica fume used in this experimental work as cement replacement was obtained from Sika Company. Nano silica used in this experimental work is a white powder brought from National Center for Building and Housing Research. Their chemical composition is given in table-I.

Table-I: Chemical composition of GGBFS, SF and Nano silica

Element	GGBFS	SF	NS
CaO % by mass	37.1	0.21	0.14
Al ₂ O ₃ % by mass	7.5	1.03	0.15
SiO ₂ % by mass	18.5	96.89	99.16
Fe ₂ O ₃ % by mass	27.9	0.56	0.05
MgO % by mass	5.24	0.15	0.12
MnO % by mass	1.37	-	-
Na ₂ O % by mass	1.06	0.17	0.3
P ₂ O ₅ % by mass	0.635	-	0.01

Alkali activator consists of sodium hydroxide pellets (NaOH with 99% purity) and sodium silicates solution consists of 0.45 solids (Na₂O + SiO₂) and 0.55 of water. The ratio between SiO₂:Na₂O is approximately 2.5 by mass. Specific gravity of used sodium silicates solution is 1.6 from manufacturer data sheet. To improve the workability of

fresh concrete Super plasticizer type "G" (sikament R2004) brought from sika company was used in this investigation. The coarse aggregate used in this experimental work was locally available in Egypt of size 10mm and down. Fine aggregate of fineness modulus 2.89 and specific gravity 2.56 is used.

B. Preparation of Alkaline solution

Sodium hydroxide pellets is dissolved in clean tap water to make a solution with required concentration (14 mole). Since the molecular weight of sodium hydroxide is 40, in order to prepare a solution of 14molar concentration (14x40) 560 gram of sodium hydroxide pellets is dissolved in 1litter of water. Alkaline solution used by two methods with different temperatures:

- The first method, the alkaline activator mixture was prepared a day before mixing because the reaction of sodium hydroxide liberates heat so sodium hydroxide is stand for 24 hours in order to cool down after that it mixed with sodium silicates in ratio of 1:2.5 (NaOH:Na₂SiO₃) and the alkali mixture were mixed together until the solution became homogenous. It's called normal activator.
- The second method, sodium hydroxide solution stands for 3 hours then mixed with sodium silicates and used. So in this method the activator temperature is around 50 °c. It's called hot activator.

C. Preparation of mix

Several trials were performed before arriving at the final mixes. The current experimental program deals with six different Geopolymer concrete mixes to study the effect of using local GGBFS with and without SF to produce geopolymer concrete with different GGBFS & SF content. The GGBFS replacement by SF by ratios (0, 10, 20, 30, 40 & 50) %. Then the optimum sample is defined by its method of curing and developed by adding nano silica in ratios 1, 2 & 3% of the total weight of cementitious materials. All trial mixes has the same Alkali activator/binder ratio but further water was added if needed for workability and the same cement content. Molarity of NaOH for all trial mixes is 14M. The ratio between Na₂SiO₃: NaOH is also constant and equal 2.5. Mixing proportions of geopolymer concrete is shown in table-II.

Table -II: Mixing proportions of geopolymer concrete

	Mix No.	Sand Kg/m ³	Dolomite Kg/m ³	Silica fume Kg/m ³	GGBFS Kg/m ³	Nano silica	NaOH Kg/m ³	Na ₂ SiO ₃ Kg/m ³	S.P Lit/m ³
M1	1	600	1120	-	650	-	44.1	110.2	13.36
M2	2	600	1120	65	585	-	44.1	110.2	13.36
M3	3	600	1120	130	520	-	44.1	110.2	13.36
M4	4	600	1120	195	455	-	44.1	110.2	13.36
M5	5	600	1120	260	390	-	44.1	110.2	13.36
M6	6	600	1120	325	325	-	44.1	110.2	13.36
M7	A	600	1120	128.7	514.8	6.5	44.1	110.2	13.36
M8	B	600	1120	127.4	509.6	13	44.1	110.2	13.36
M9	C	600	1120	126.1	504.4	19.5	44.1	110.2	13.36

D. Mixing and casting

The following procedure was adopted for preparation of the mixes:

- Silica fume and GGBFS is mixed for 2 minutes in the mixer.

- Half of the activator is added in the mixer and rest of the alkali activator is mixed with super plasticizer.
- A bout half of the remaining activator is added to the paste in mixer and mixing together for 3 minutes.
- Sand and aggregate is added in the mixer with the remaining alkali activator and mixed for 3-4 minutes
- Cleaning the moulds and applying oil
- Fill the moulds with concrete in three layers each layer 5cm and damping each layer 25 damp using damping rod.
- Samples then kept in rest period for 24 hours after that the samples demoulded and cured.

E. Curing

Geopolymer concrete samples which casted using normal activator demoulded after 24 hours and cured in room temperature. But geopolymer concrete samples in stage two which casted using hot activator were demoulded after 24 hours and half of samples were placed in room temperature till testing, it's the ambient temperature curing. And the other half of samples were cured in oven at temperature 75°C for 24 hours then kept in room temperature till testing to study the effect of using oven curing in case of hot activator. Nano silica samples (M7, M8 & M9) cured only in oven at temperature 75°C for 24 hours then kept in room temperature till testing.

III. RESULTS AND ANSLYSIS

A. Compressive strength

In this study, GPC cubes of size 150x150x150mm were used to test the compressive strength at 7&28 days for both

Table -III: Results of compressive strength at ages 7& 28 days using hot activator with different methods of curing

Mix no.	Type of concrete	Average comp. strength for oven cured at 7 days	Average comp. strength for ambient cured at 7 days	Average comp. strength for oven cured at 28 days	Average comp. strength for ambient cured at 28 days
M1	100%GGBFS	35	30	40	35
M2	90%GGBFS+10 %SF	50	45	55.1	50
M3	80%GGBFS+20 %SF	61.05	55.8	68.5	63.08
M4	70%GGBFS+30 %SF	62.48	58.1	69.64	65
M5	60%GGBFS+40 %SF	57.56	52.1	63	57.8
M6	50%GGBFS+50 %SF	46.6	38	51.7	44

normal activator temperature when samples cured in ambient temperature and hot activator temperature when samples cured in oven at temperature 75°C and in ambient temperature. "M1" consider the control trial mix then silica fume is added in different ratios (10, 20, 30, 40 & 50)% as partial replacement of GGBFS. The results at which samples failed are recorded in table III and IV. The maximum compressive strength is observed at 30% replacement of silica fume. The maximum compressive strength is 62.48MPa and 69.64MPa at age 7 and 28 days respectively when using hot activator and cured samples in oven. But when using hot activator and cured samples in ambient temperature the compressive strength is 58.1MPa and 65MPa at ages 7 and 28 days. So curing samples in oven at temperature 75°C shows improvement in compressive strength by 7.5% and 7.1% at 7 and 28 days respectively as the temperature accelerated the geopolymerization reaction. There is an improvement in compressive strength of concrete as the addition of silica fume in concrete increases up to 30% the strength and durability of concrete increase and improves its physical, chemical and micro structure. It fills the pores between aggregate and geopolymer cement and reduces the porosity of concrete. Also, silica fume considers highly reactive pozzolanic material with high surface area and high amount of SiO₂ as silicon oxides reacts with hydroxide ions (OH⁻) which exists in the activator and forms extra aluminum silicates gel which acts as a binder. So the internal transition zone "ITZ" enhanced by the physical and chemical effects of silica fume.

Table-IV: Results of compressive strength using normal activator and curing samples in ambient temperature

Mix No.	Type of concrete	Average comp. strength for ambient cured at 7 days MPa	Average comp. strength for ambient cured at 28 days MPa
M1	100% GGBFS	10	19.7
M2	90% GGBFS+10% SF	15.4	29.2
M3	80% GGBFS+20% SF	20	35.62
M4	70% GGBFS+30% SF	23.24	38
M5	60% GGBFS+40% SF	18	32.2
M6	50% GGBFS+50% SF	12.7	25.5

B. Splitting tensile strength

GPC cylinders of size 150mm diameter and 300mm height were used to test splitting tensile strength at 28 days. The load at which sample finally failed is recorded in tables V and VI for both normal activator temperature when samples cured in ambient temperature and hot activator temperature when samples cured in oven at temperature 75°C and in ambient temperature. The maximum increase in splitting tensile strength is observed at 30% replacement of silica fume. The splitting tensile strength is 7MPa when using hot activator and cured samples in oven. But when using hot activator and cured samples in ambient temperature the maximum splitting tensile strength is 6.3MPa. So curing samples in oven at temperature 75°C shows improvement in splitting tensile strength by 11%. There is an increase in splitting tensile strength of concrete up to 30% of silica fume replacement because of the high pozzolanic nature of silica fume and its void filling ability.

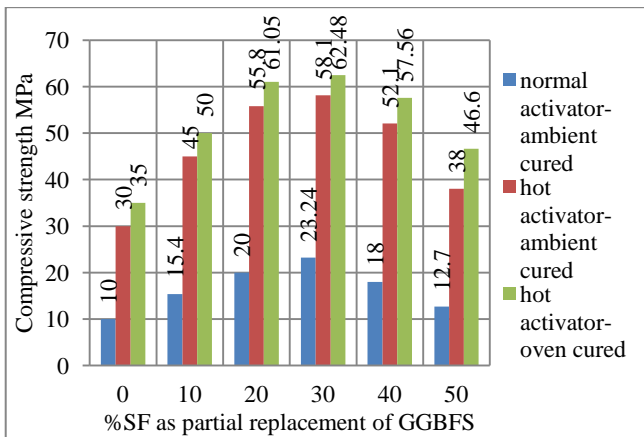


Fig.1: Comparison between the results of 7-days compressive strength.

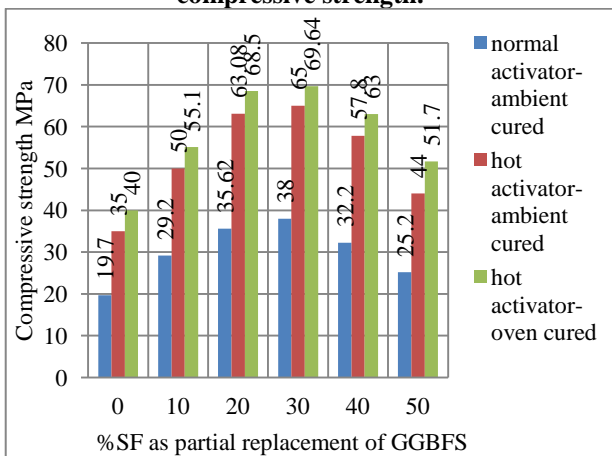


Fig. 2: Comparison between the results of 28-days compressive strength.

Table-V: Results of splitting tensile strength using hot activator

Mix no.	Type of concrete	Splitting strength for oven curing MPa	Splitting strength for ambient temp. MPa
M1	100%GGBFS	4	3.3
M2	90%GGBFS + 10%SF	5.3	4.7
M3	80%GGBFS + 20%SF	6.6	5.9
M4	70%GGBFS + 30%SF	7	6.3
M5	60%GGBFS + 40%SF	6.2	5.5
M6	50%GGBFS + 50%SF	4.6	3.9

Table-VI: Results of splitting tensile strength using normal activator

mix. no.	type of concrete	Splitting strength for ambient temperature MPa
M1	100%GGBFS	1.8
M2	90%GGBFS + 10%SF	2.7
M3	80%GGBFS + 20%SF	3.4
M4	70%GGBFS + 30%SF	3.7
M5	60%GGBFS + 40%SF	3.1
M6	50%GGBFS + 50%SF	2.3

C. Modulus of Elasticity

GPC cylinders of size 150mm diameter and 300mm height were used to test modulus of elasticity at 28 days. The load at which sample finally failed is recorded in tables VII and VIII for both normal activator temperature when samples cured in ambient temperature and hot activator temperature when samples cured in oven at temperature 75°C and in ambient temperature. The maximum increase in modulus of elasticity is observed at 30% replacement of silica fume. The maximum modulus of elasticity is 32612.5MPa when using hot activator and cured samples in oven. But when using hot activator and cured samples in ambient temperature the maximum modulus of elasticity is 29875.5. So curing samples in oven at temperature 75°C shows improvement in modulus of elasticity by 9.2%.

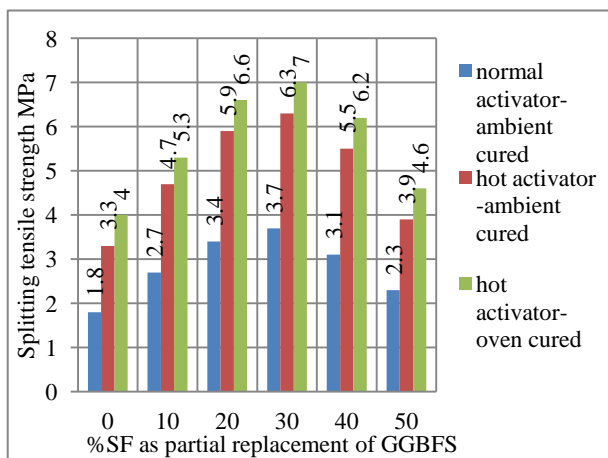


Fig. 3: Comparison between the results of splitting tensile strength.

Table-VII: Results of modulus of elasticity using hot activator

Mix no	type of concrete	Young's modulus for oven cured samples MPa	Young's modulus for ambient temperature cured samples MPa
M1	100%GGBFS	23534.8	19426.4
M2	90%GGBFS + 10%SF	28036.36	24542.7
M3	80%GGBFS + 20%SF	31137.5	28148.98
M4	70%GGBFS + 30%SF	32612.5	29875.5
M5	60%GGBFS + 40%SF	30430.5	27028.18
M6	50%GGBFS + 50%SF	25500	21905.5

Table-VIII: Results of modulus of elasticity using normal activator

Mix. No.	type of concrete	Young's modulus for ambient temperature cured samples MPa
M1	100%GGBFS	11235.84
M2	90%GGBFS + 10%SF	13989.3
M3	80%GGBFS + 20%SF	16607.9
M4	70%GGBFS + 30%SF	18224.05
M5	60%GGBFS + 40%SF	15866.5
M6	50%GGBFS + 50%SF	12486.13

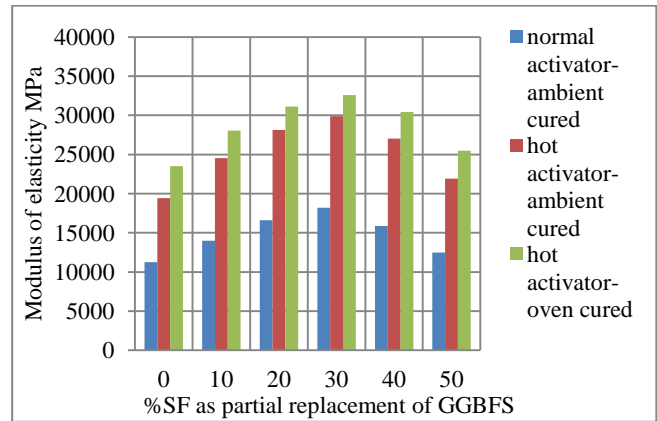


Fig. 4: Comparison between the results of modulus of elasticity

D. Nano silica

The optimum sample which consists of (70%GGBFS+30%SF) developed by adding nano silica with ratios 1, 2 and 3% and the results of compressive strength at ages 7 and 28 days, splitting tensile strength and modulus of elasticity showed in table-IX.

Table-IX: Results of compressive strength at ages 7 and 28 days, splitting tensile strength and modulus of elasticity with different nano silica content

Mix no.	%NS	comp. strength at 7 daysMPa	comp. strength at 28 days MPa	splitting tensile strength MPa	Youngs modulus MPa
M7	1	66.2	71.77	7.5	33998.6
M8	2	75.11	86.71	8.85	35981.18
M9	3	45.6	55.03	6.4	30572.21

The results showed that up to 2% nano silica gives higher results in compressive strength, splitting tensile strength and modulus of elasticity but after that the results decreases according to agglomerate effect. This is due to addition of nano silica increases strength and durability of concrete more than micro silica because of its smaller size than micro silica. Also its high surface area make it reacts faster and forms extra gel which acts as binder between aggregate and cement grains. Although the increase of nano silica

above certain rate (2%) gives negative effect because of agglomerate effect as the high energy that emits in the hydration process make cement grains congregate together that causes more pores in concrete so that it decreases its mechanical properties and durability.

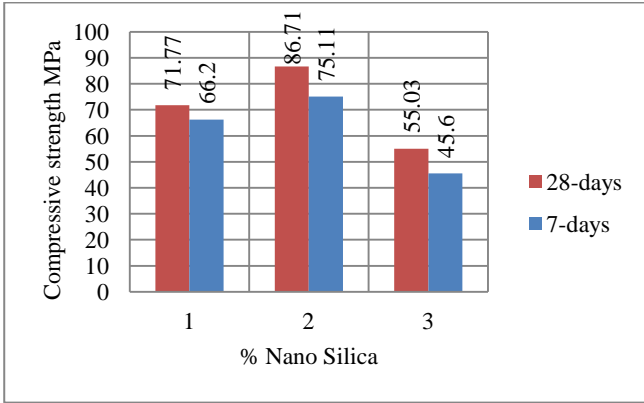


Fig. 5: Results of compressive strength at age 7 and 28 days when adding nano silica

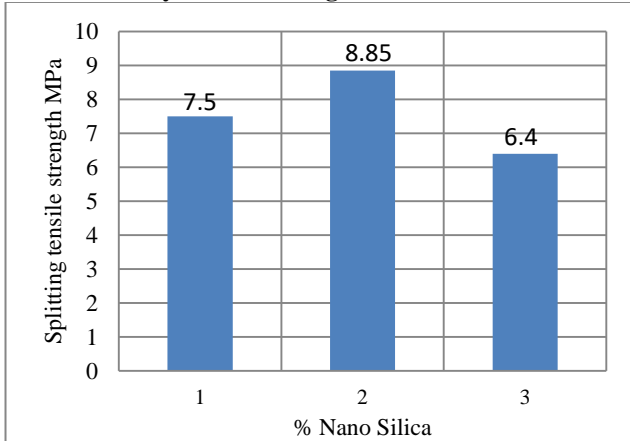


Fig. 6: Results of splitting tensile strength when adding nano silica

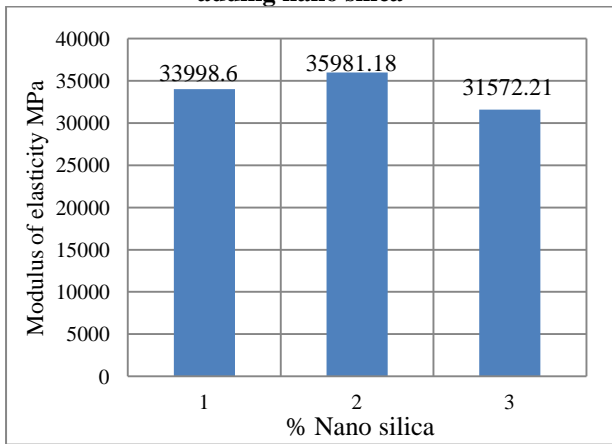


Fig.7: Results of modulus of elasticity when adding nano silica

E. Stress strain curves

Stress – strain curves is plotted for samples casted by hot activators temperature only (samples cured in ambient temperature and at oven without nano silica and samples cured at oven with adding nano silica). Stress-strain curves showed that, the mixture which containing 2% nano silica gives higher stresses so it is stiffer than the other mixtures. This is due to addition of nano silica increases strength and durability of concrete more than micro silica because of its smaller size than micro silica. Also its high surface area make it reacts faster and forms extra gel which acts as binder between aggregate and cement grains. Also, for samples which casted without nano silica it was found that samples which cured in oven give maximum stresses than samples cured in ambient temperature. So curing samples

in oven makes it stiffer. The maximum increase in stress for samples without nano silica was observed at 30% replacement of silica fume.

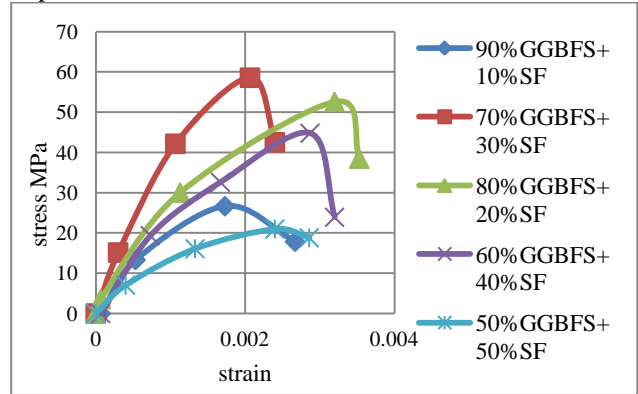


Fig.8: Stress-Strain curves for geopolymer concrete mixes cured in oven at temperature 75°C.

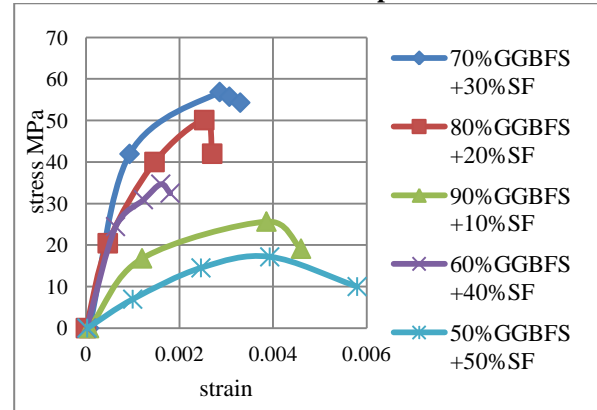


Fig.9: Stress-Strain curves for geopolymer concrete mixes cured in ambient temperature.

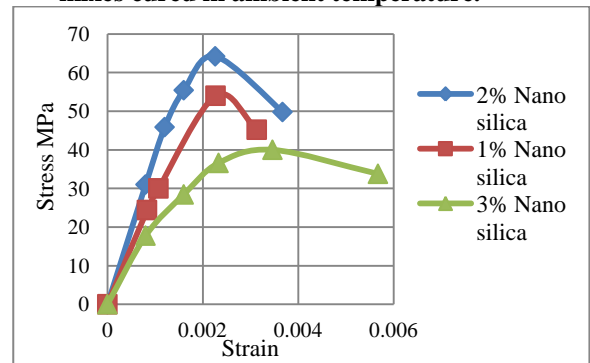


Fig. 10: Stress-Strain curve for nano silica mixes.

IV. CONCLUSIONS

This paper presents the development of high strength geopolymer concrete. The binder used in this study is SF & GGBFS in different ratios. Control trial mix "M1" is the mixture without silica fume. Samples casted by different temperature activator and cured by different methods "oven curing at 75°C & ambient temperature curing" then tested for mechanical properties. Optimum sample defined with its method of curing and developed by adding nano silica in different ratios (1, 2 & 3)% of the total weight of cementitious materials. The results showed that:-



Development of High Strength Geopolymer Concrete using Nano Silica

- The results showed that for different activators temperature and for different methods of curing the mixture which reached high compressive strength, splitting tensile strength and modulus of elasticity was observed at 30% replacement.
- Using hot activator temperature gives higher results than using normal activators temperature.
- In case of using hot activator, curing samples in oven at temperature 75°C is more efficient than curing samples in ambient temperature.
- Adding nano silica to the optimum geopolymer concrete sample up to 2% increasing the results but after this ratio the results decreases.
- The results of compressive strength approximately increased by 75% as average at age 28 days when using hot activator.
- The results of splitting tensile strength and modulus of elasticity approximately increased by 72% when using hot activator.
- In compressive strength the percentage of increase ranges between (7.5 to 22)% at 7 days from ambient to oven curing and ranges between (7.1 to 17.5)% at 28 days.
- In compressive strength the results increased from 7 to 28 days by ratios from 9.4 to 14.3% for oven curing and from 10.9 to 16.67% for ambient temperature curing.
- In splitting tensile strength when using hot activator the percentage of increase ranges between (11 to 21)% from ambient to oven curing.
- In modulus of elasticity when using hot activator the percentage of increase ranges between (9.16 to 21.1)% from ambient to oven curing.

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