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Mechanical properties and durability of GGBS geopolymer mortar for M sand and river sand

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Abstract

The increasing demand for sustainable construction materials has led to a renewed interest in geopolymer technology, which utilizes industrial by-products to create eco-friendly alternatives to traditional cement-based products. This study focuses on geopolymer mortar developed using Ground Granulated Blast Furnace Slag (GGBS), a by-product of iron production, known for its pozzolanic properties. GGBS-based geopolymer mortar not only addresses environmental concerns associated with cement production but also enhances the mechanical and durability characteristics of the final product The fly ash based geopolymer motor set slowly in an ambient temperature and needs heat curing. To overcome this limitation, GGBS powder is used as a cementious material which shows considerable gain in strength.. In this research, various formulations of GGBS-based geopolymer mortar were created by varying the ratio of GGBS to fine aggregates, the concentration of alkaline activators (such as sodium hydroxide and sodium silicate), and the curing conditions, including temperature and duration. The primary objective was to optimize these parameters to achieve superior performance characteristics in terms of compressive strength, flexural strength, and durability. The properties of geopolymeric binder prepared using the ground-grounded blast surface without using any conventional cement has been investigated. The individual properties of the GPM for 1:3 ratio, such as compressive strength, split tensile, water absorption, sportivity and acid resistivity test were determined as perrelevant Indian standards .Cubes of size (70.6X 70.6X 70.6)mm were casted and cured in ambient condition for molarity 4M 6M and 8M with M sand. Compressive strength for 3, 7, 28 days was studied along with oven curing for 28 days. The result shows increase in strength for 8M M sand. The sorptivity test was conducted and also water absorption was studied, it shows decreased results for 8M M sand. Good and effective results were obtained for acid resistivity test and also the results obtained for porosity, sportivityand water absorption of geopolymer motor specimens also indicates the durability of geopolymer motors.

Keywords: Geopolymer mortar (GPM); Ground Granulated Blast Furnace Slag (GGBS); Alkaline activator; Sorptivity

1. Introduction

Geopolymer mortar is an innovative and sustainable building material that has garnered significant attention in recent years due to its environmentally friendly properties and superior performance characteristics. Unlike traditional cement-based mortars, which rely heavily on the calcination of limestone (calcium carbonate) to produce clinker, geopolymer mortar utilizes industrial by-products such as fly ash, slag, or metakaolin. These materials undergo a chemical reaction with alkaline activators to form a durable binding matrix, making geopolymer mortar a more sustainable alternative for construction.

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The concept of geopolymer technology was first introduced by chemist Joseph Davidovits in the 1970s, and since then, it has evolved into a viable solution for addressing several challenges in modern construction. One of the most significant advantages of geopolymer mortar is its reduced carbon footprint. The production of traditional Portland cement is responsible for approximately 8% of global CO_2 emissions, primarily due to the energy-intensive processes involved. In contrast, geopolymer mortars can significantly lower these emissions by reusing industrial waste materials and requiring less energy for production [1].

Geopolymer mortars exhibit several beneficial properties that make them suitable for a wide range of applications. They possess excellent mechanical strength, high resistance to chemical attacks, and superior durability against extreme environmental conditions, such as heat and moisture. These characteristics make them ideal for use in infrastructure projects, such as bridges, tunnels, and pavements, as well as in residential and commercial buildings. Furthermore, geopolymer mortars can be tailored to meet specific performance requirements by adjusting the composition of the raw materials and the activators used, offering versatility in their application. Construction industry is seeking for other alternatives such as recycled aggregates, industrial wastes in order to meet the need in concrete manufacturing. The alternative for fine aggregate i.e., for natural river sand is M sand being used in this project.

2. Materials and Methodology

2.1. Materials

Cementious Material [GGBS]: Slag is a by-product produced during the manufacturing of pig iron and steel, by quenching molten iron slag from a blast furnace in water or steam, the product is then dried and ground into a fine powder.The cooling process of slag is responsible mainly for generating different types of slags required for various end-use consumers. Although, the chemical composition of slag may remain unchanged, physical properties vary widely with the changing process of cooling. As a sustainable material, GGBS contributes to more environmentally friendly construction practices, making it a popular choice in modern engineering and construction projects. It is primarily made up of silica, alumina, calcium oxide, and magnesia (95%). Other elements like manganese, iron, sulphur, and trace amounts of other elements make up about other 5% of slag. The exact concentrations of elements vary slightly depending on where and how the slag is produced. In the present study 100% by mass of binders was replaced with GGBS.

Table 1 Physical properties of GGBS

Sl No	Properties	Test Results
1.	Specific Gravity	2.83
2.	% Particles retained on 90μ Sieve	Nil

Fine aggregates. Two types of fine aggregates are used in this study.

- Natural sand, i.e. fine aggregate resulting from natural disintegration of rocks. Locally available river sand is used. The fine aggregate should be free from all organic and inorganic matters.
- Crushed stone sand [M sand], i.e. fine aggregate produced by crushing hard stone/granite stones in required grading.

The aggregates passing through 4.75 mm sieve and retained on 600 μm sieve, conforming to Zone II as per IS: 383-1970 was used as fine aggregate in the present study. The physical requirements of these aggregates such as Fineness modulus, and Specific Gravity and Bulk modulus in accordance with IS: 2386-1963[2].

Table 2 Physical properties of M Sand& River Sand

Properties	**M Sand**	**River Sand**
Specific Gravity	2.42	2.80
Fineness modulus	3.58	3.60
Bulk Density [kg/m3]		
Loosely packed	1.556	1.470
Compacted	1.754	1.585
Bulking[%]	41.18	35.29
Void Ratio	0.36	0.475
Grading Zone	Belongs to grade Zone II of IS 383-1970	Belongs to grade Zone II of IS 383-1970

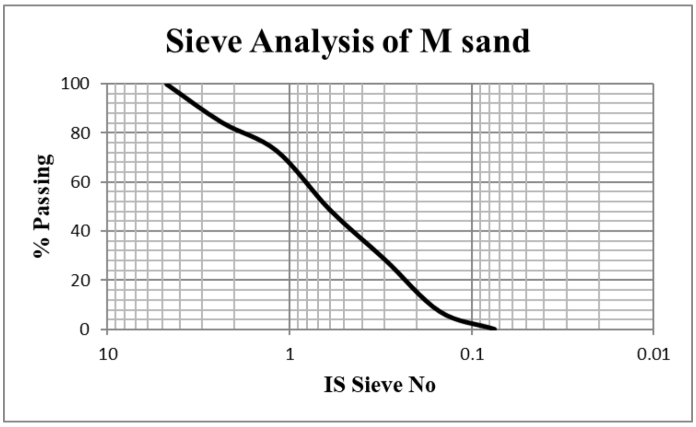

Figure 1 Sieve Analysis of M sand

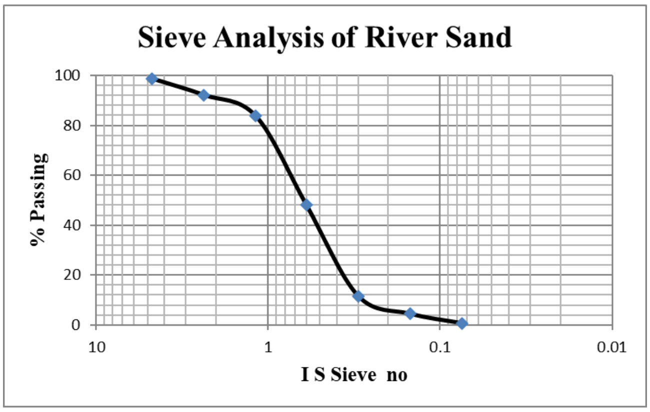

Figure 2 Sieve Analysis of River sand

Alkaline Activator: An alkaline activator in GGBS (Ground Granulated Blast-furnace Slag) mortar enhances the reactivity of the slag, promoting a quicker setting time and improved strength. Common activators include sodium hydroxide and sodium silicate, which facilitate the formation of binding compounds, resulting in durable and sustainable construction materials. The alkaline activator liquid used was a combination of sodium silicate (Na2SiO3) solution and sodium hydroxide (NaOH) solution. The sodium hydroxide is obtainable in flakes and pellets form. In this research 97% to 98% pure sodium hydroxide pellets were used. The sodium silicate is available in solution form and has a chemical composition of Na_2O=18%, SiO_2=34% and water=48% by mass.The laboratory tap water was used for the preparation of this alkaline solution[3].

2.2. Methodology

The methodology involves prepartion0of alkali activator solution, mixing of mortar, casting of mortar, curing ofmortar and test.

Preparation of Alkali solution: Laboratory grade materials are procured and calculations are made for different molarities. Alkaline solution is prepared using sodium hydroxide, sodium silicate and water. Portable water is measured for required quantity in a container and to0this calculated amount of sodium hydroxide pellets is added to it based on its molarity and stirred properly to avoid solidification at the bottom of the container. After dilution of NaOH, sodium silicate shall be mixed with the solution and properly stirred. This is an exothermic reaction and generated heat more than 500ºC and thus this reaction has to complete before mixing with constituents of mortar, or else it will create thermal cracks in mortar. This alkali activator solution is chemically very active and this has to handle properly. This solution has to be kept for 24 hours so that, reaction will be complete and solution completely cools down

Figure 3 Preparation of Alkaline Solution

Mixing, Casting and Curing: As there are no code provisions for the mix design of geopolymer mortar, the density of geo-polymer mortar is assumed as 2100 Kg/m^3. The other calculations are done by considering the density of mortar for mortar ratio 1:3.Ratio of sodium silicate to sodium hydroxide is taken as 2.5 .The conventional method used in the making of normal mortar is adopted to prepare geopolymer mortar. To prepare Geopolymer mortar, at least one day earlier alkaline activator solution is to be prepared. According to mix proportion (Molarity) sodium hydroxide pellets are dissolved in water and mixed with sodium silicate solution, to make alkalineactivator.The various constituents of GPM are weighed properly according to mix design. Binder material GGBS and fine aggregates are mixed properly to get uniform dry mix. Alkaline activator solution is mixed well to this dry mix with trowel until good mortar mix is obtained. Transfer Geopolymer mix into steel moulds of size (cube 70.6mmx70.6mmx70.6mm) in 3 layers with good compaction. After 24 hours, specimens are demoulded and were left to air drying at room temperature until tested (ambient curing)[4].

Figure 4 Preparation of GPM Cubes

Figure 5 GPM cubes are kept in sun shade for ambient curing

3. Result and Discussions

3.1. Compression Test

Cube specimens of size 70.6mmx70.6mmx70.6mm were taken out after ambient curing and tested at the ages of 3, 7 and 28. Specimens are tested as per IS 516-1959(part 5). While testing the cubes are placedat right angle to that as cast. Without shock the load is applied gradually till the failure of the specimen happens and thus the compressive strengthwas found. The point at which specimen fails is considered as maximum load (N), and the surface area exposed to load is cross section of the specimen. Thus compression strength is calculated by the formula,

$$\text{Compressive strength or stress} = [\text{Load} / \text{Area}]\ N/mm^2$$

Figure 6 Molarity comparison of GPM with M Sand

Table 3 Compressive strength of GPM with M Sand

Molarity	Compressive Strength in N/ mm²			
	Age in Days			
	Ambient Curing			Oven Curing
	3	7	28	28
4 M	16.25	22.27	42.33	43.66
6M	20.86	24.57	45.27	50.96
8M	25.58	28.39	56.84	63.05

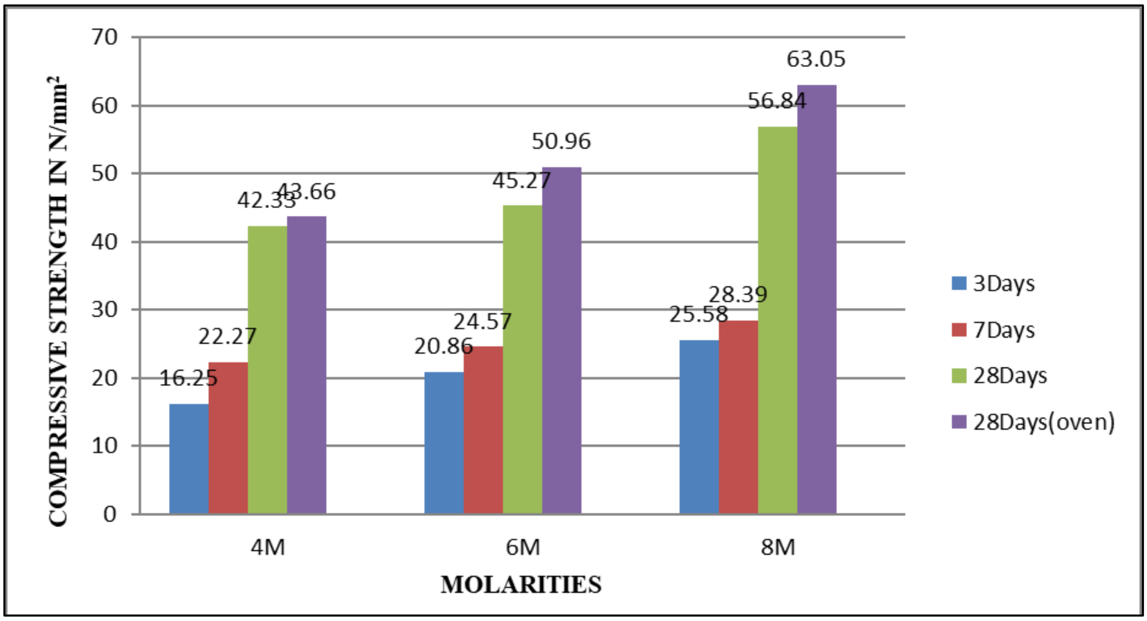

Figure 7 Compressive strength of GPM with M Sand

3.2. Molarity comparison of GPM with River Sand:

Table 4 Compressive strength of GPM with River Sand

Molarity	Compressive Strength in N/ mm²			
	Age in Days			
	Ambient Curing			Oven Curing
	3	7	28	28
4 M	11.9	19.93	39.85	42.2
6M	17.04	22.87	41.79	46.87
8M	20.06	25.88	49.25	51.96

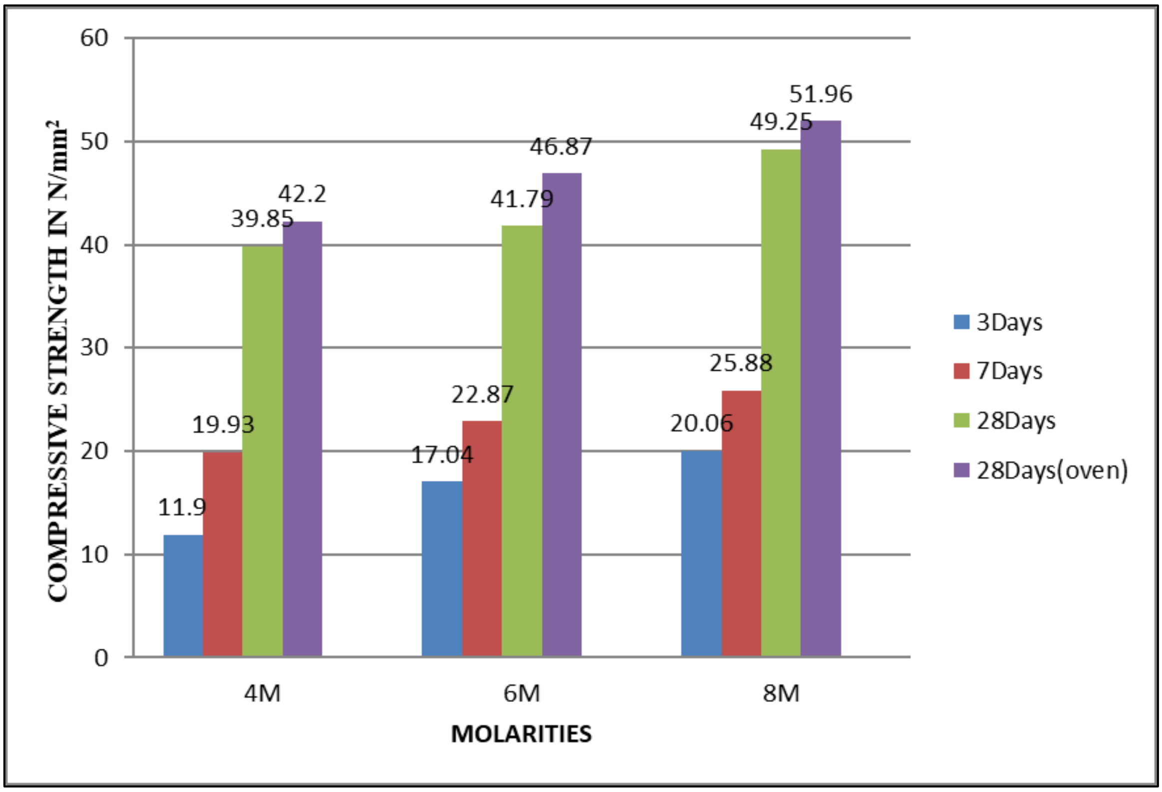

Figure 8 Compressive strength of GPM with River Sand

3.3. Split Tensile Test

It is an indirect method of finding out the tensile strength of mortar that is by subjectingthe cylinder specimen to a lateral compressive force. For these test cylinders of size 100mm diameterand 200mm long were casted and afterh24 hour's thellspecimens are demoulded and cured in ambient condition for 28 days. Then the specimens were tested in universal testing machine by placing horizontally (IS code 5816-1999)[5].

Split Tensile Strength, $fsp=2P/\pi dl$

Where, P= Load applied on specimen inllN
l = Specimen length in mm
d= Diameter of cylinder in mm

3.4. Molarity comparison of GPM with River Sand and M sand

Table 5 Split Tensile Test for different Aggregates

Molarity	Split tensile test in N/ mm² after 28days of ambient curing	
	Fine Aggregates	
	River Sand	M Sand
4 M	3.27	3.82
6M	4.5	4.9
8M	5.02	5.12

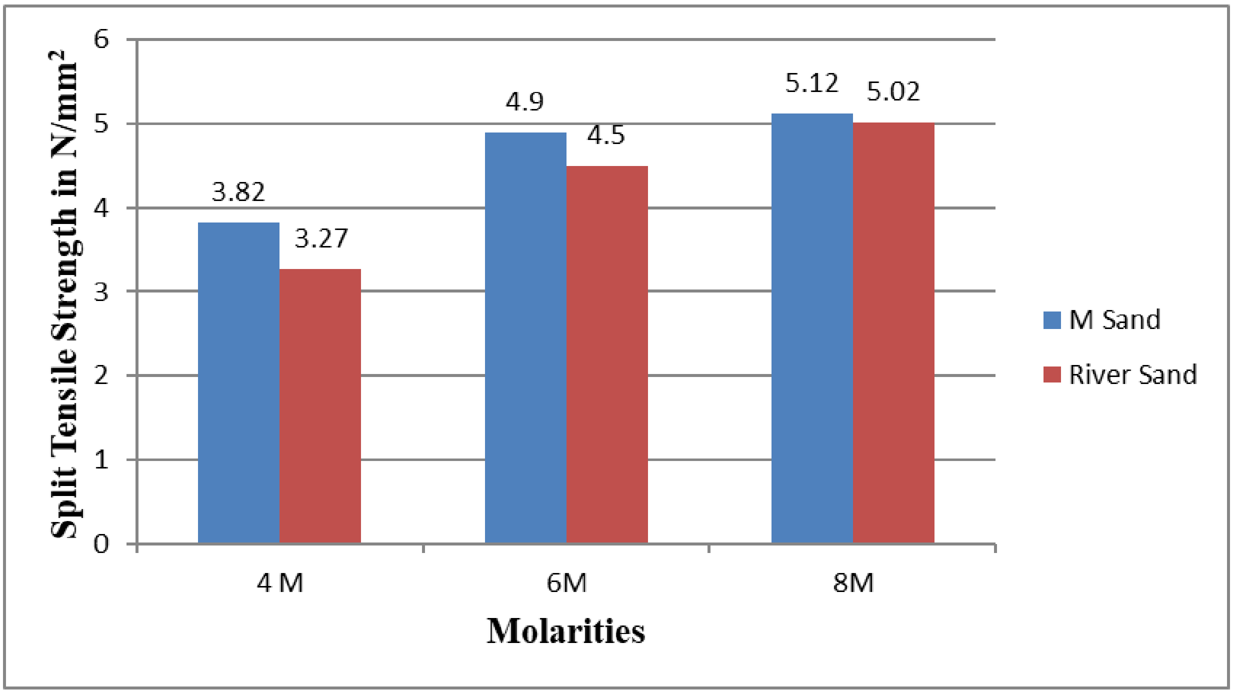

Figure 9 Split Tensile Test for different Aggregates

3.5. Water Absorption

Water absorption test is conducted for determining the relative water absorption property of mortar. It is measured by measuring the increase in mass as a percentage of dry mass and is reported as the percentage in weight.

$$\text{Water absorption} = (W2\text{-}W1)\ W1X100$$

Where
W= Weight of specimen after 28 days curing.
W1=Weight of oven dried specimen.
W2= Weight of specimen after immersed in water.

Figure 10 Set up for water absorption test

3.6. Molarity comparison for River Sand

Table 6 Water Absorption for River Sand

Type of Mortar	Notation	Initial Weight (kg)	Oven dry Weight(kg)	Weight after immersion	% Gain	Avg % Gain
GPM (4M)	GPMR-	626	613	680	10.90	10.72
	GPMR-2	721	708	769	8.61	
	GPMR-3	608	592	667	12.66	
GPM (6M)	GPMR-1	785	777	808	3.98	4.21
	GPMR-2	772	763	797	4.45	
	GPMR-3	792	783	816	4.21	
GPM (8M)	GPMR-1	852	846	859	1.53	1.92
	GPMR-2	859	854	866	1.40	
	GPMR-3	783	778	800	2.83	

3.7. Molarity comparison for M Sand:

Table 7 Water Absorption for M Sand

Type of Mortar	Notation	Initial Weight (kg)	Oven dry Weight(kg)	Weight after immersion	% Gain	Avg % Gain
GPM (4M)	GPMM-1	655	647	675	4.32	4.78
	GPMM-2	617	607	639	5.27	
	GPMM-3	677	671	703	4.76	
GPM (6M)	GPMM-1	769	762	788	3.41	3.06
	GPMM-2	774	767	788	2.73	
	GPMM-3	763	754	777	3.05	
GPM (8M)	GPMM-1	809	803	815	1.49	1.78
	GPMM-2	801	796	808	1.50	
	GPMM-3	767	760	778	2.36	

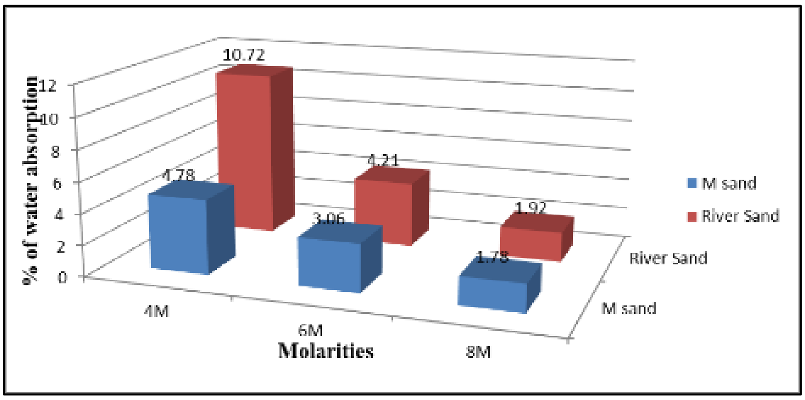

Figure 11 Water Absorption for different Aggregates

3.8. Water Sorptivity Test

The sorptivity test determines the rate of capillary rise absorption of water by mortar cube. The test amounts the rate of absorption of water by capillary suction of unsaturated mortar placed in contact with water. After 28 days ambient curing, specimens are dried in oven at 65°c for 48 hours. Then these specimens are kept on water in such a manner that only the lowest 2 to 5mm of the cube is submerged. The increase in the mass of the specimen with time is note down[6].

There is a relation of form.

$$I = S\sqrt{t}\text{ , therefore } S = I/t^{1/2}$$

Where,
S= Sorptivity in gm/ mm^2/min0.5
I = ΔW/Ad, I=Cube mass increase perdunit area (gm/mm^2).
ΔW = change in weight ($W2-W_1$) in gm
W_2 = final weight of the specimen after taken out from the water in gm
W_1 = initial dry weight of the specimen in gm
A = Specimen surface area in mm^2
D = Water density
t = Time in which specimen immersed in minute

3.9. Molarity comparison for River Sand:

Table 8 Sorptivity for River Sand

Type of Mortar	Notation	Oven dry Weight(kg)	Weight after immersion	Sorptivity 10^{-3}	Avg Sorptivity in 10^{-3}mm/min^0.5
GPM (4M)	GPMR-1	699	761	2.27	2.72
	GPMR-2	624	701	2.82	
	GPMR-3	572	656	3.08	
GPM (6M)	GPMR-1	793	823	1.10	1.26
	GPMR-2	747	783	1.32	
	GPMR-3	768	805	1.36	
GPM (8M)	GPMR-1	816	841	0.916	0.92
	GPMR-2	780	804	0.879	
	GPMR-3	796	822	0.952	

3.10. Molarity comparison for M Sand:

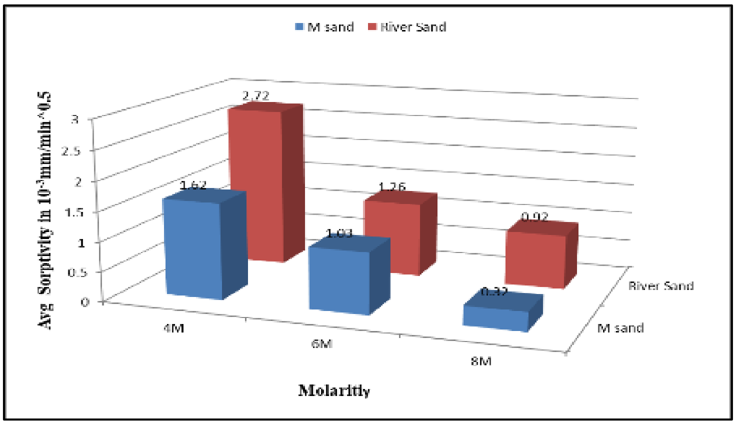

Figure 12 Sorptivity for different Aggregates

Table 9 Sorptivity for M Sand

Type of Mortar	Notation	Oven dry Weight(kg)	Weight after immersion	Sorptivity 10^{-3}	Avg Sorptivity in 10^{-3}mm/min^0.5
GPM (4M)	GPMM-1	654	703	1.79	1.62
	GPMM-2	699	740	1.50	
	GPMM-3	639	682	1.58	
GPM (6M)	GPMM-1	743	768	0.916	1.03
	GPMM-2	766	789	0.842	
	GPMM-3	696	732	1.32	
GPM (8M)	GPMM-1	825	836	0.403	0.32
	GPMM-2	790	819	0.106	
	GPMM-3	793	805	0.440	

3.11. Dry Density Of Mortar Cube

To conduct this test mortar cube of size 70.6x70.6x70.6 mm, are casted and cured for 28 days in ambient condition. These cubes are weighed after taking out from curing. The density is calculated by dividing this weight of mortar cubes by volume of that cubes[7]

Dry density is calculated using the formula

$$\text{Density}=W1/V1$$

Where V1= (70.5X70.5X70.5) m3

3.12. Dry density

Table 10 Dry Density for river sand and M sand with different Molarities

Molarity	Material	Weight of the cubes			Avg Weight in grm	Volume cm^3	Density grm/ cm^3
		1	2	3			
4M	GGBS+RS	655	617	677	650	351.89	1.85
	GGBS+MS	721	686	708	705	351.89	2.00
6M	GGBS+RS	769	774	763	769	351.89	2.18
	GGBS+MS	785	772	792	783	351.89	2.23
8M	GGBS+RS	809	801	795	802	351.89	2.28
	GGBS+MS	852	859	789	833	351.89	2.36

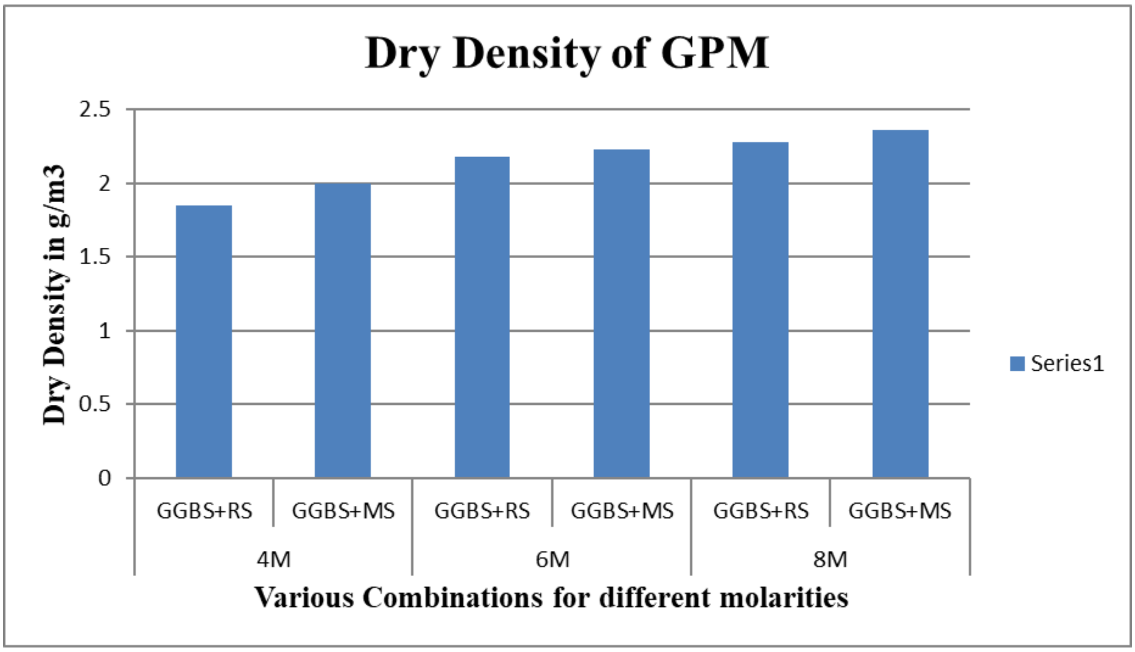

Figure 13 Density for various combinations with different molarities

3.13. Acid Resistivity Test

This test is conducted to know the resistance of GPM against acidic condition. To conduct this test mortar cubes of size 70.6x70.6x70.6mm are casted and cured in ambient condition for 28rdays. After curing, the weight of the specimens is taken. These cubes are immersed in acid bath tub which should be prepared early by dissolving 50grms of concentrated sulphuric acid for each litre of water. Then the cubes were placed in the acid bath tub for 30days. After 30days the cubes were taken out and dried it completely. Note down the final weights of the cubes and note down its residual compressive strength. The weight difference shows the resistance of the mortar to the acid[8-9].

Figure 14 Set up of acid resistivity test

Figure 15 Mortar cubes after acid attack

3.14. For river sand

Table 11 Acid attack test results of River sand

Molarity	Initial weight of the cubes before acid attack in grams	Weight of the cubes after 30days acid attack in grams	Compressive strength of the cubes after acid attack in N/mm^2
4M	819	815	38.91
6M	839	819	40.01
8M	865	845	47.36

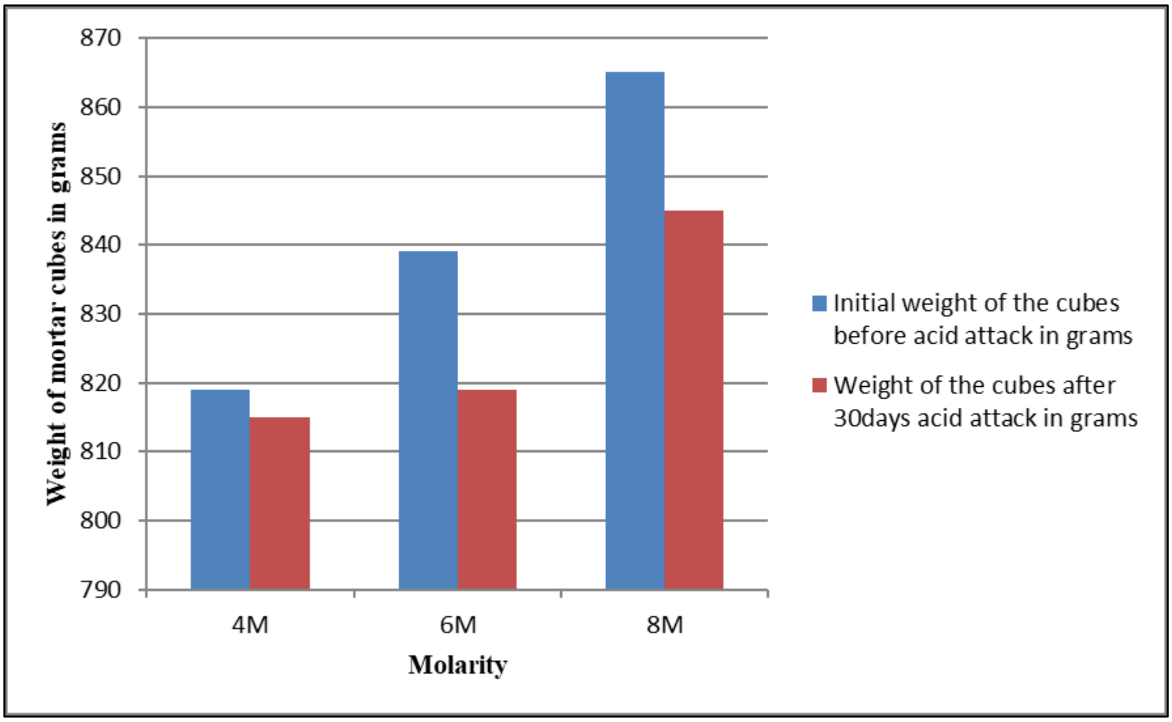

Figure 16 Acid attack test results of River sand

3.15. For m sand

Table 12 Acid attack test results of M sand

Molarity	Initial weight of the cubes before acid attack in grams	Weight of the cubes after 30days acid attack in grams	Compressive strength of the cubes after acid attack in N/mm²
4M	851	847	40.20
6M	845	838	43.85
8M	855	850	53.23

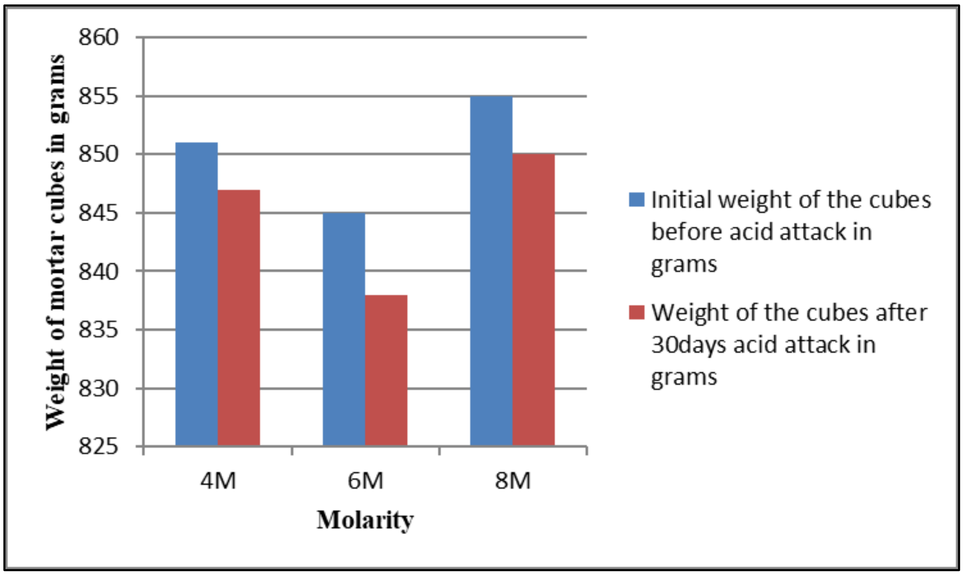

Figure 17 Acid attack test results of M sand

4. Conclusion

This paper presented the study of GGBS based Geopolymer mortar. From the above experimental results the following conclusions are drawn:

- As molarity increased the compressive strength is also increased i.e, as concentration of sodium hydroxide and sodium silicate is more in the alkaline solution results in elevated compressive strength of GPM .
- Due to short supply of river sand, M sand can be effectively used in construction because GPM with M sand has given good results compared to river sand.
- GGBS based mortar has given sufficient good results in ambient curing only, it does not require steam curing and this property has made easy to apply this in cast in situ structure.
- Indirect tensile strength or split tensile strength of GGBS-based geopolymer has higher value and also the value increases with increase in molarity.
- Water Absorption rate is less in GPM and decreased as molarity increased.
- As concentration of sodium hydroxide increased, workability of geopolymer mortar decreases.
- Cubes prepared with 8 molar sodium hydroxide have been note down reduced sorptivity when compared to the cubes made with 4 and 6 molar sodium hydroxide.
- Density of GPM is more. M sand based GPM is denser than compared to river sand.
- The residual compressive strength of GPM when exposed in sulphuric acid has a direct relationship with alkali content. As molarity increased the samples shows higher residual compressive strength.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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