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EXPERIMENT AND SIMULATION STUDY ON REINFORCED GEOPOLYMER CONCRETE SLAB UNDER IMPACT LOADING

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ABSTRACT

Geopolymer concrete is an eco-friendly material that has the potential to replace conventional cement-based concrete. Geopolymers are inorganic aluminosilicates and can be used to replace cement. In this study, Geopolymer concrete is produced by mixing Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), Silica Fume (SF), alkaline mixture, fine aggregate, and coarse aggregate. Strength is imparted to geopolymer concrete through polymerization in alkaline media. The alkaline solution consists of NaOH and Na_2SiO_3 in the ratio of 1:2.5. A proper geopolymer mix was selected by testing among multiple sets of cube, cylinder, and prism specimens of different geopolymer mixes. The Geopolymer Mixes selected were 50% GGBS + 40% FA + 10% SF, 60% GGBS + 30% FA + 10% SF, 70% GGBS + 20% FA + 10% SF, and 80% GGBS + 10% FA + 10% SF. Each mix was cast for three molarities 8M, 12M, and 16M of NaOH solution. 70% GGBS + 20% FA + 10% SF mix with 16M NaOH solution (Na2SiO3/NaOH =2.5:1) showed the best performance in terms of compressive strength and flexural strength. It was found that the compressive strength and flexural strength increased with molarity. The splitting tensile strength increased with an increase in GGBS percentage. Workability decreased with increasing molarity. All Geopolymer Concrete (GPC) mixes showed better performance than M30 mix conventional concrete. Hence 70% GGBS + 20% FA + 10% SF mix with 16M NaOH solution was selected for further study of the GPC slab. Five Reinforced Geopolymer Concrete (RGPC) slabs were casted and their dynamic performance were studied under impact loading. A series of drop hammer impact tests were carried out to investigate the impulse of RGPC slabs under a single impact. The variation of the peak impact force of slab under varying drop heights and varying reinforcement ratios were studied experimentally. The impact force's time history and the slab surface's failure characteristic were recorded. In addition, a parametric study was conducted using numerical models based on the finite element method (FEM) considering parameters: drop height, reinforcement ratio, depth of slab, and location of impact. The study observed that RGPC has the potential to replace concrete as a structural material.

Keywords - Geopolymer concrete, Impact Loading, Reinforced Geopolymer Concrete Slab

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1. INTRODUCTION

The construction industry is an important part of every economy and plays a major role in economic development as well as job creation. However, the sector is very much dependent on cement as its basic component, which uses so much of resources and releases high amounts of greenhouse gases (GHGs). It is estimated that in the production of one ton of cement, about two tons of raw materials are consumed, and approximately one ton of carbon dioxide (CO_2) and nitrogen oxides (NO) gases are emitted. According to IPCC (International Panel for Climate Change) data, about two billion tons of GHGs are emitted annually as a result of the production of cement, and cement production is responsible for about 6% of the world's anthropogenic GHG gas emissions annually. Further cement production also causes air, water, and soil pollution, consumption of huge amounts of raw materials, over-exploitation of natural reserves, deterioration of the environment, and alteration of ecosystems. Moreover, the process is highly energy intensive.

Hence, there is an urgent need for a green alternative to conventional concrete, especially in the context of increasing urbanization, and development and the International Energy Agency's proposal to go carbon neutral by 2050. Here comes the significance of geopolymer concrete (GPC) which forms a green, sustainable alternative to conventional concrete.

French researcher Joseph Davidovits first proposed the word geopolymer in the 1970s. Geopolymers are inorganic alumino-silicates forming long-range networks. These geopolymers in the presence of alkali activators undergo the polymerization process in order to give GPC. GPC acquires strength through the polymerization of aluminosilicates in alkaline media. The best part of GPC is, it consumes geopolymers, which are waste products of various industries. Some of the most commonly found geopolymers are ground granulated blast furnace slag (GGBS) - which is a waste product of iron industry, fly ash (FA) – which is a waste product from thermal powerplants, silica fume (SF) – which is a waste product of silicon industry, rice husk ash (RHA) – a byproduct of burning rice husk, metakaolin – sourced from clays etc. Various studies suggest that using GPC instead of concrete leads to sustainable construction, longer service life, low carbon emissions, reduction in global warming potential, reduction of virgin materials usage, remarkable life cycle cost saving, and recycling of industrial waste.

Despite several positives of GPC, it is not widely used in regular construction activities. They are used mainly as precast concrete elements or as a coating in highly reactive environments. This paper aims to assess its usage as a structural component, which in this case is a slab, and to study its behavior under impact loading.

In natural disasters, security incidents and military strikes, the structural components may be subjected to impact loads such as explosion, falling rock collision, resulting in bending failure, bending shear failure, and even brittle shear failure. Damage to structural elements can cause instability or even collapse of the entire structure. The dynamic response of the reinforced concrete (RC) components under the impact load is affected by impact energy, reinforcement ratio, component size, impact position, and other factors, which is a complex mechanical process.

The impact behavior of structural components also gives insights into their strength and ductility which are the most important characteristics of any structural component. Also, studies of reinforced GPC slabs subjected to impact loading are still relatively rare. The project proposes to provide a geopolymer mix that can wholly replace cement and can be used in construction, including structural elements such as beams, columns, slabs, panels, etc, without any compromise in its structural performance.

In this project, the behavior of the Reinforced GPC (RGPC) slab subjected to impact loading is analyzed using a combination of experiments and simulation studies. Further, a parametric study is conducted using a combination of experiments and simulation studies considering the parameters: drop height of impactor, reinforcement ratio of slab, slab depth, and location of impact.

The main objectives are

- To design a Geopolymer Mix, selecting among various constituents of geopolymers available and casting reinforced geopolymer concrete slab specimens of the resulting best mix.
- To experiment with reinforced geopolymer concrete slabs under Impact Loading.
- To study its behavior under Impact Loading and to analyse using FEA software.
- To check if GPC can be used as structural elements.

This paper aims to find a sustainable geopolymer mix that can be used to replace cement wholly from the concrete composition without any compromise in its structural characteristics. The proposed mix needs to be cured only under ambient curing conditions for 28 days, similar to conventional concrete. The geopolymer mixes are studied for their compressive strength, splitting tensile strength, and flexural strength, and the best-performing mix was selected to cast 5 reinforced GPC slab specimens. The slabs were subjected to drop weight impact tests, for a single impact and the dynamic response of the slab was studied using sensors. The time histories of impact force were plotted and compared for different drop heights and reinforcement ratios experimentally. Further, a parametric study was conducted numerically using Abaqus software, considering parameters: drop height, reinforcement ratio, slab depth and impact point location. Finally, the results are analysed.

2. MATERIALS AND METHODS

2.1 Materials

The constituents used in this experiment include Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Fly Ash (FA), fine aggregate, coarse aggregate, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), and cement (to make a reference set for comparison to M30 conventional concrete).

GGBS is selected as the primary element in the geopolymer mix. GGBS is whitish-grey in color. SF has the property of imparting strength in the mix. SF is white in color. FA has the property of improving the workability of the mix. FA is grey in color.

The fine aggregate used in the project is locally sourced M-sand. The coarse aggregate used in the project is well-graded aggregate with a maximum size of 20mm. The tests of fine aggregate were conducted as per IS-650:1996 & IS-2386:1968. The tests for coarse aggregate were conducted as per IS-2386:1963. The physical properties of fine and coarse aggregate are provided in Table 1.

Sodium Hydroxide (NaOH) was bought in pellet form and was mixed with water to form solutions of different molarities. Mixing of NaOH with water is a highly exothermic reaction. Hence NaOH pellets were dissolved in water 24 hours prior to casting. 1M solution requires 40g of NaOH mixed in 1L of water. Thus, 8M, 12M, and 16M require 320g, 480,g, and 640g of NaOH mixed in each liter of water.

Sodium Silicate (Na_2SiO_3) was bought in industry-grade solution form. It is a viscous liquid. It is responsible for the hardening of the geopolymer mix and geo-polymerization. This was added to the NaOH solution 1 hour prior to casting.

Cement was used to cast nine cubes, four cylinders, and three prisms of M30 mix, thus, comparing the results of geopolymer mixes to a basic conventional concrete mix of M30 grade.

Fig 1: GGBS, Silica Fume, and Fly Ash

Fig 2: Mixing of Na_2SiO_3 and NaOH solution

Table 1 Physical properties of fine and coarse aggregates.

Properties	Fine aggregate (Sand)	Coarse aggregate (Gravel)
Specific gravity	2.36	2.71
Bulk density (kg/L)	1.66	1.7
Fineness modulus	3.3	5.81
Maximum nominal size(mm)	-	20
Void Percentage (%)	37	38

2.2 Mix Design

The trial and error method of mix design was selected. And four trial geopolymer mixes were considered: 1) 50% GGBS + 40% FA + 10% SF; 2) 60% GGBS + 30% FA + 10% SF; 3) 70% GGBS + 20% FA + 10% SF and 4) 80% GGBS + 10% FA + 10% SF. Three molarities of the NaOH solution selected are 8M, 12M, and 16 M. The ratio of (Na_2SiO_3/NaOH solution) was selected as: 2.5:1 for the entire project. The design was done according to IS 10262. The design procedure was in accordance with the M30 concrete mix. All the unknown values were assumed in accordance with IS 10262, as for the design of a normal M30 mix.

Nine cubes, six cylinders, and three prisms were casted for each Geopolymer Mix and each Molarity and tested for compressive strength, splitting tensile strength, and flexural strength respectively.

(a)

(b)

(c)

Fig 3: (a) Testing for compression in Compression Testing Machine (b) Testing for splitting tensile strength in Compression Testing Machine (c) Testing for flexural strength in Flexural Strength Testing Machines

The results of testing of compressive strength, splitting tensile strength, and flexural strength are given in table 2, 3 and 4 respectively.

Table 2 Average Compressive Strength of cubes tested in 7,14 and 28 days.

S.No	Geopolymer Mix	Molarity	7 days	14 days	28 days
1.	50% GGBS+40% FA+10% SF	8M	22	31.3	46.7
		12M	24.1	35.7	49.5
		16M	26	36.6	53.2
2.	60% GGBS+30% FA+10% SF	8M	27.5	37	47.3
		12M	29.8	38.2	51.4
		16M	31	39.4	54.6
3.	70% GGBS+20% FA+10% SF	8M	32.7	40.6	49.7
		12M	33.4	42.5	52.4
		16M	36.3	49.8	60.1
4.	80% GGBS+10% FA+10% SF	8M	27	37.5	48
		12M	29	40	51
		16M	32	42.2	54
	M30 Mix Conventional Concrete		20.5	26.2	31.4

Table 3 Average Splitting Tensile Strength of cubes tested in 7 and 28 days.

S.No	Geopolymer Mix	Molarity	7 days	28 days
1.	50% GGBS+40% FA+10% SF	8M	0.38	1.2
		12M	0.45	1.9
		16M	0.56	2.3
2.	60% GGBS+30% FA+10% SF	8M	0.71	1.7
		12M	1.11	2.25
		16M	1.53	2.7
3.	70% GGBS+20% FA+10% SF	8M	1.76	2.2
		12M	1.95	2.5
		16M	2.1	3.6
4.	80% GGBS+10% FA+10% SF	8M	1.79	2.4
		12M	1.83	2.8
		16M	2.3	3.7

	M30 Mix Conventional Concrete		0.15	0.289

Table 4 Flexural Strength of cubes tested in 7 and 28 days.

S.No	Geopolymer Mix	Molarity	7 days	28 days
1.	50% GGBS+40% FA+10% SF	8M	1.8	2.4
		12M	2	2.7
		16M	2.2	3
2.	60% GGBS+30% FA+10% SF	8M	1.9	2.6
		12M	2.3	3.3
		16M	2.7	4.4
3.	70% GGBS+20% FA+10% SF	8M	2.4	3.2
		12M	2.7	3.8
		16M	3.2	5.6
4.	80% GGBS+10% FA+10% SF	8M	1.1	2
		12M	1.4	2.4
		16M	1.9	3.3
	M30 Mix Conventional Concrete		1.8	3.1

All GPC mixes showed better performance than M30 mix conventional concrete. The geopolymer mix- 70% GGBS + 20% FA + 10% SF with 16M NaOH solution (Na_2SiO_3/NaOH =2.5:1) showed the best performance in terms of compressive strength, equivalent to 60MPa. This was twice the value of the compressive strength of M30 mix conventional concrete.

70% GGBS + 20% FA + 10% SF mix showed the best strength with 16M NaOH solution (Na_2SiO_3/NaOH =2.5:1). → Hence this mix is selected for further study of GPC slab. Hence all the initial tests were conducted for this geopolymer mix and the data obtained are listed in Table 5.

Table 5 Physical properties of 70%GBS+20%FA+10%SF geopolymer mix.

Properties	Geopolymer Mix
Physical Properties	
Specific gravity	2.83
Standard consistency	38%
Setting time Initial	23 min
Setting time Final	180 min
Compressive Strength	
At 7 days	36.3N/mm^2
At 28 days	60.1 N/mm^2
Splitting Tensile Strength	3.6 N/mm^2
Flexural Strength	5.6 N/mm^2
Colour	Light Gray
Curing Condition	Ambient Curing

The mixing of NaOH pellets with water releases a lot of heat. Hence NaOH pellets were mixed in water 24 hours prior to casting. Na_2SiO_3 was added to the NaOH solution one hour prior to casting. The ratio of NaOH: Na_2SiO_3 was kept 1:2.5 throughout the experiment.

After carrying out the initial tests, five slab specimens were casted each with a slab depth of 100mm and sides 500mmx500mm. Three specimens were of the same slab depth and reinforcement ratio of 2.4% (8mm dia bars were used as reinforcement). One specimen was of reinforcement ratio 1.3% (6mm dia bars were used as reinforcement), and last specimen had a reinforcement ratio of 3.7% (10mm dia bars were used as reinforcement).

3. EXPERIMENTAL SETUP

To study the dynamic response of the RC slab under impact loading, a series of drop hammer impact tests were carried out. In a series of drop hammer impact tests, the response of the GPC slabs to impact loading was examined. After the impact, the specimen surface was observed, and the time history curves of the impact force were recorded using sensors attached to the slabs.

3.1 Test Specimens

A total of five slabs were cast, each having a size of 500x500x100mm^3. All slabs were cast using geopolymer mix- 70%GGBS+20%FA+10%SF. The mix proportion was carried out in accordance with IS-10262:2009, and the design was done equivalent to that of M30. The design mix had the ratio of Geopolymer: Fine Aggregate: Coarse Aggregate = 1:2.21:3.327. All specimens were water cured under ambient curing conditions for 28 days. The temperature at which curing was done varied between 25-35^{o}C.

The standard slab specimen under this experiment had the following properties:

Depth of slab = 100mm

Reinforcement Ratio = 2.4% (8mm dia)

Drop Hammer Height = 1.5m

Location of impact → @ reinforcement intersection as shown in the figure 4.

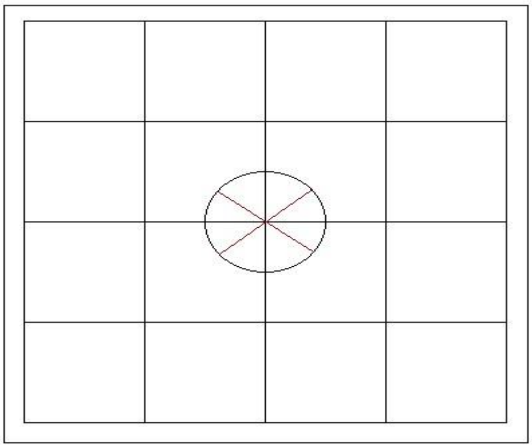


Fig 4: Location of Impact

Design of test specimen

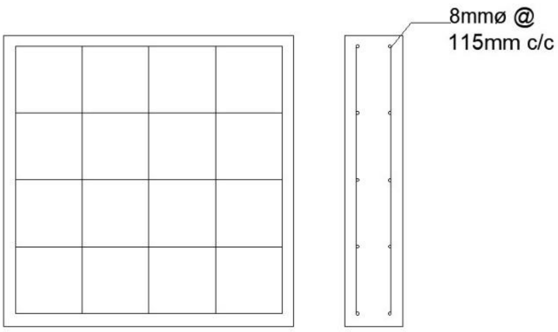


Fig 5: Design of specimens

Three standard slab specimens were cast. Two other slabs having varying reinforcement ratio was also cast. Those were having a reinforcement ratio of 1.3%, lower than the standard specimen, and others having a reinforcement ratio of 3.7%, higher than the standard specimen. The variation in reinforcement ratio was achieved by varying the cross-section of rebar used (6mm dia bar - 1.3% reinforcement ratio; 8mm dia bar – 2.4% reinforcement ratio; 10mm dia bar – 3.7% reinforcement ratio). The three standard specimens were used to study the variation of impact force with drop height as the varying parameter.

A parametric study was conducted using Abaqus CAE software to study the variation of impact force, deflection, and thus the dynamic response of the slab by considering parameters: drop height of hammer, reinforcement ratio, depth of the slab, and location of impact.

Fig 6: Slab mould with reinforcement

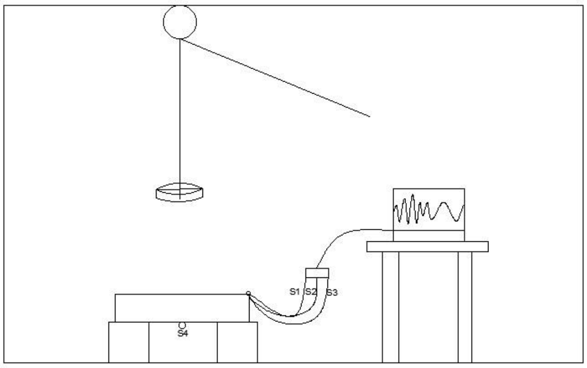
Fig 7: Fresh GPC in mould

3.2 Testing Process

The drop hammer was tied in such an arrangement it could be pulled with the help of a rope to the desired height. This drop hammer was used to apply the impact load. The drop hammer weighed 5kg. Four wired sensors were attached to the slab under testing to measure the linear acceleration. Three sensors were attached to both ends of sides of the slab and one nearer to the middle portion. One sensor was temporarily fixed to the bottom center portion of the slab before the application of load.

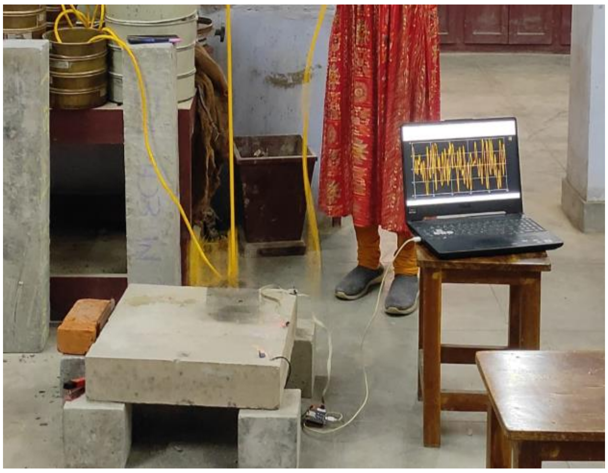
The slabs were supported using Cubes with sides 150mm on all four corners and hence the boundary condition was assumed to be simply supported. The sensors converted the impulse of the slab to numerical values with the help of C-Sharp software. Later the values are obtained in Excel sheets, which could be used to plot graphs. The values of linear acceleration obtained could be multiplied with the mass of drop weight (5kg) to easily calculate impact force.

The arrangement was made in such a way that the center of the impactor collided with the center of the slab. A rope was used to raise the drop hammer to its intended height, after which it fell freely and struck the GPC slab. After that, the hammer was set back to the desired position, the extent of damage of the specimen and the time history curve of the impact force generated by the first impact was recorded, and the procedure was repeated for the second impact. The instrumentation of the entire testing system is depicted in Figures 6,7 and 8.



(a)

(b)



(c)

Fig 8: (a) Schematic diagram showing the arrangement of GPC slab, sensors attached to micro-controller which is attached to PC (b)Arrangement for testing (c) Impact testing of slab

4. SIMULATION STUDY

Due to the restrictions of time and test methods, twelve FEM model was developed using ABAQUS CAE to further investigate the dynamic mechanical characteristics of the GPC slab. All simulated cases were conducted under identical circumstances as the aforementioned drop hammer experiments. The reasoning of the numerical model was confirmed by comparing the test and simulation results of the impact force time history curve. The peak impact force, GPC slab deflection, and vertical stress were explored.

In the simulation study, the energy and mass loss of the drop weight was neglected and was assumed that the gravitational potential energy of the drop mass is purely converted into kinetic energy. Further, a parametric study is carried out using the FEM models. The four parameters considered in the study include drop height, reinforcement ratio, depth of slab and location of impact. The parametric study is discussed in detail in the results and discussion section.

4.1 FEM Model Establishment

The finite element model consisted of three parts: impactor, GPC slab, and rebar. The whole simulation was done in a Dynamic Explicit model. Slab and rebar were made deformable solids, while the impactor was made a discrete rigid shell-type element with its center as the reference point. Two materials were defined, that is, concrete and steel. Concrete were assigned properties under Concrete Damage Plasticity model. Properties were assigned to rebar and slab. The whole reinforced GPC slab was assembled in the Assembly module

4.2. Setting Contact Mode and Constraint Conditions.

Surface-to-surface contact was assigned between the top face of the slab and the bottom face of the impactor. Friction coefficients were provided for the contact. The rebars in the slab were set to be embedded in the slab. The boundary condition on all four corners of the slab was set to be simply supported.

4.3. Applying Impact Load.

In the whole impact process, the energy and mass loss of the drop hammer was ignored so that its gravitational potential energy was purely converted into kinetic energy, and it is easy to know that the impact velocity of the drop hammer reaching the GPC slab was V = $\sqrt{2gh}$. The drop hammer was established 1 mm above the GPC slab to reduce the solution time. In the predefined field manager, translational velocity along the y-axis (V2) was employed for defining the initial velocity of the drop hammer impact. Since the test only contained three initial hammer heights of 1 m, 1.5 m, and 2m, three models were created with an impact velocity of 4.43m/s, 5.425 m/s, and 6.26 m/s respectively. An inertia of 5kg was assigned to the impactor. Three models were created to measure the variation in reinforcement ratio. This was done by varying the cross-sectional area of the truss element (rebar). Three models were created to measure the variation in depth of the slab three models were created to measure the variation in the location of impact.

Table 6: Geopolymer Concrete Material Properties

Density(kg/m3)	Young's Modulus(N/m^2)	Poisson's Ratio
2600	38.73e+9	0.2

Table 7: Steel Material Properties

Density(kg/m3)	Young's Modulus(N/m^2)	Poisson's Ratio
7800	2.1e+11	0.3

Table 8: Concrete Damage Plasticity model parameters

Plasticity				
Dilation Angle	Eccentricity	fb0/fc0	k	Viscosity Parameter
38	0.1	1.16	0.667	0.001

5. RESULTS AND DISCUSSIONS

5.1 Compressive Strength

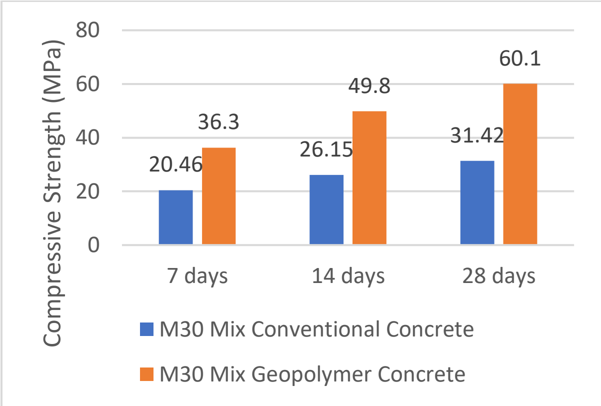


Fig 9: Compressive Strength comparison of M30 mix conventional concrete with M30 mix GPC

The test is carried out according to IS 516 -1959 to obtain compressive strength of concrete at the 7days, 14 days and 28 days. The cubes are tested using 2000 KN capacity Aimil compressive testing machine (CTM).The results are presented in Fig 7.

The 7, 14 and 28 days compressive strength of geopolymer concrete is 36.30 MPa, 49.8 MPa and 60.1 MPa.

5.2 Splitting Tensile Strength

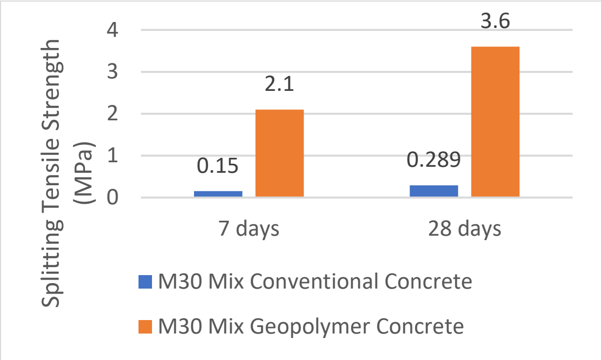


Fig 10: Splitting Tensile Strength comparison of M30 mix conventional concrete with M30 mix GPC

The test is carried out according to IS 5816 -1959 to obtain splitting tensile strength of concrete at the 7days, 14 days and 28 days. The cylinders are tested using 2000 KN capacity Aimil compressive testing machine (CTM).The results are presented in Fig 7.

The 7 and 28 days splitting tensile strength of geopolymer concrete is 2.10 MPa and 3.6 MPa.

5.3 Flexural Strength

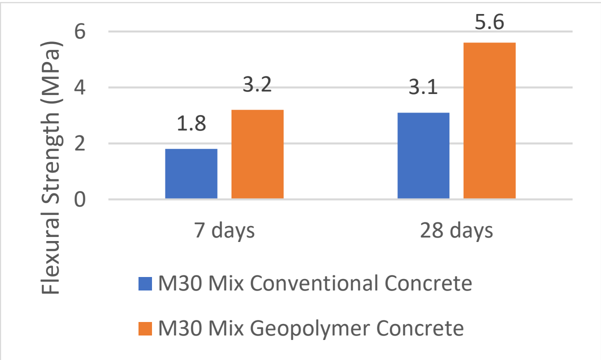


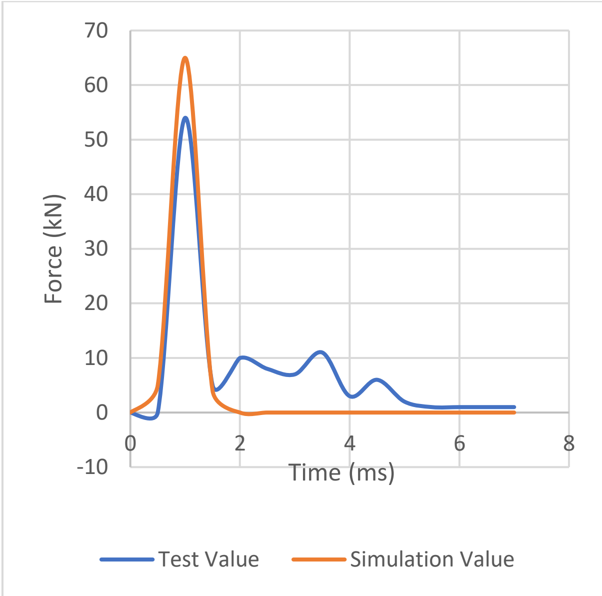
Fig 11: Flexural Strength comparison of M30 mix conventional concrete with M30 mix GPC

The test is carried out according to IS 516 -1959 to obtain strength of concrete at the 7days and 28 days. The prisms are tested using 100 KN capacity UTC-5610.MLP flexural testing machine (CTM). The results are presented in Fig 7.

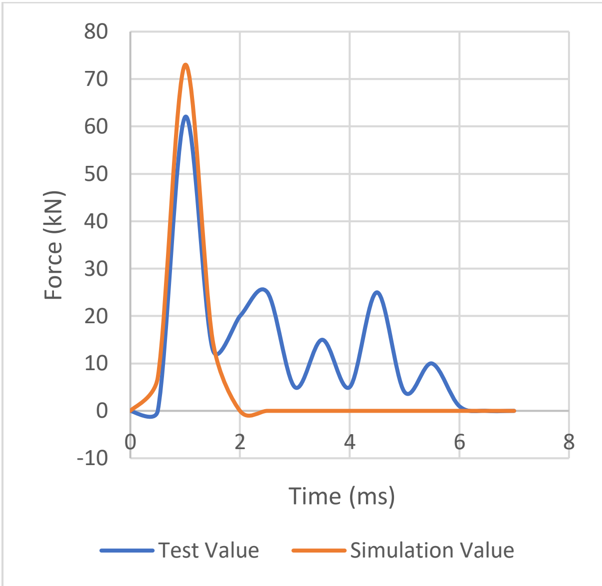
The 7 and 28 days flexural strength of geopolymer concrete is 3.2 MPa and 5.6 MPa.

5.4 Varying Drop Height

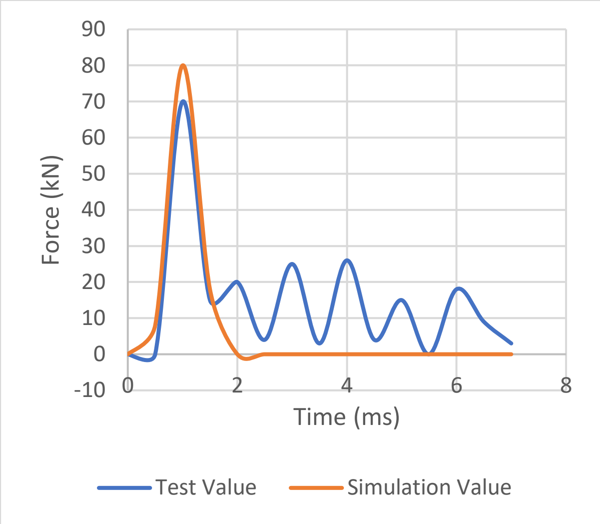
Reinforced GPC slabs of 100mm thickness with a reinforcement ratio of 2.4%, and sides 500mm, were impacted using a drop weight of 5kg from three different heights of 1m, 1.5m, and 2m. The dynamic response of the slabs under impact from each height was observed. Simulation study was also conducted using Abaqus CAE software. The impact force-time history was plotted and the deflection-time history was also plotted and the simulation and test results are compared.



(a)

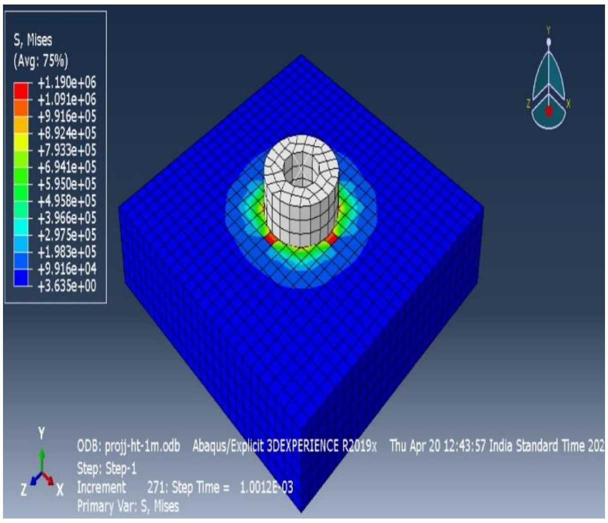


(b)

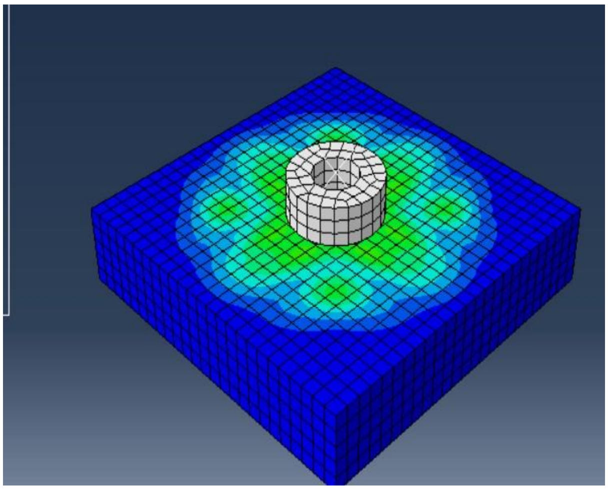


(c)

Fig 12:Comparison of impact force-time histories obtained from experiment and simulation study for an impact from a drop height of (a)1m (b)1.5m (c) 2m.



(a)



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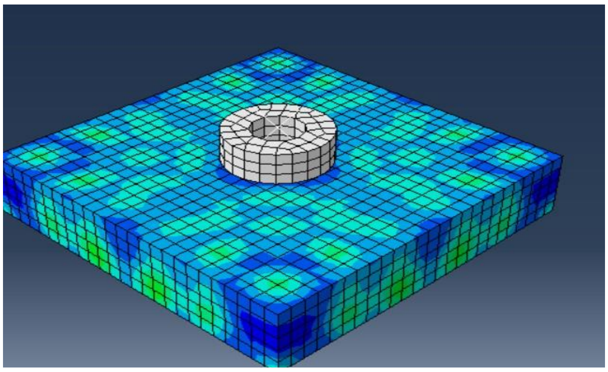
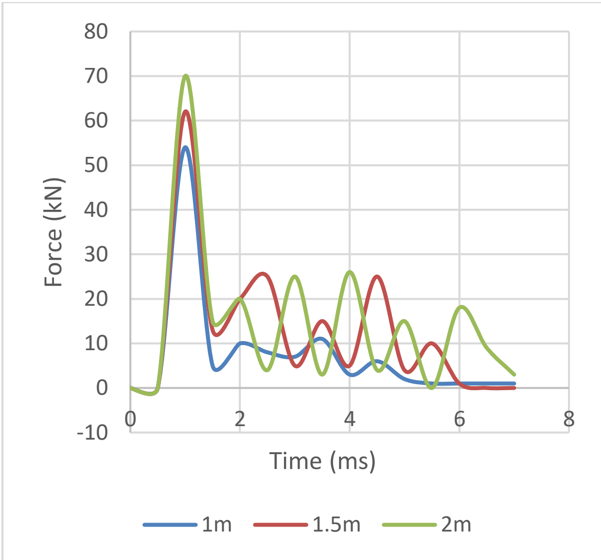
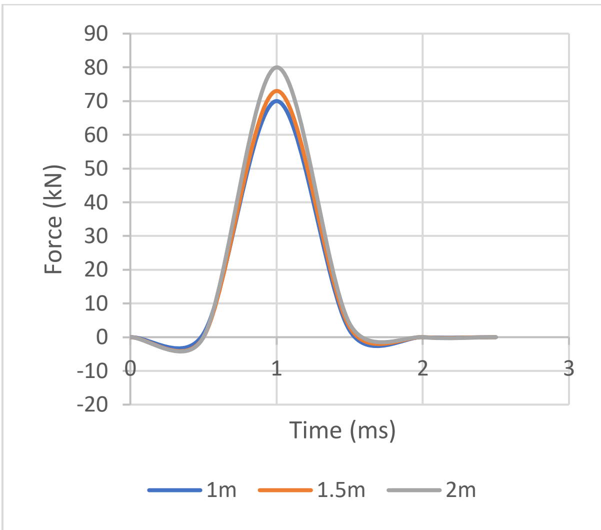


(c)

Fig 13: Stress distribution right after impact of reinforced GPC slab under an impact loading with a drop height of (a)1m (b)1.5m (c) 2m



(a)



(b)

Fig 14: Comparison of impact force-time histories for different drop heights as obtained from (a) the experiment (b) the simulation

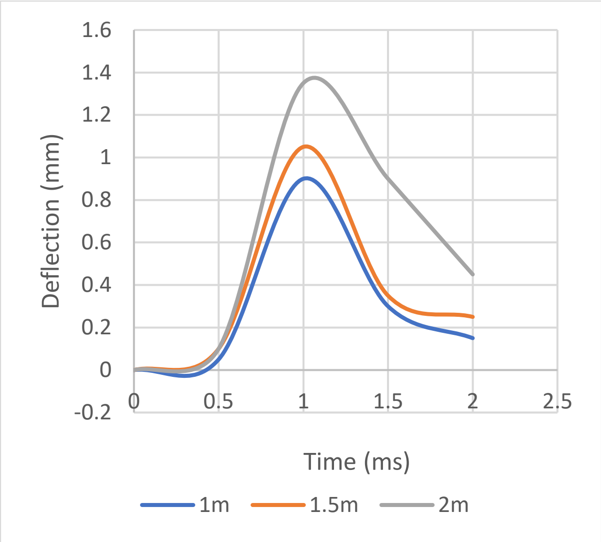
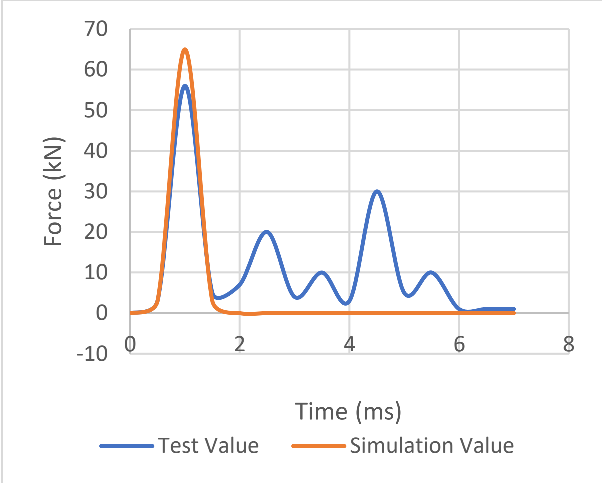


Fig 15: Comparison of displacement-time histories for different drop heights as obtained from the simulation.

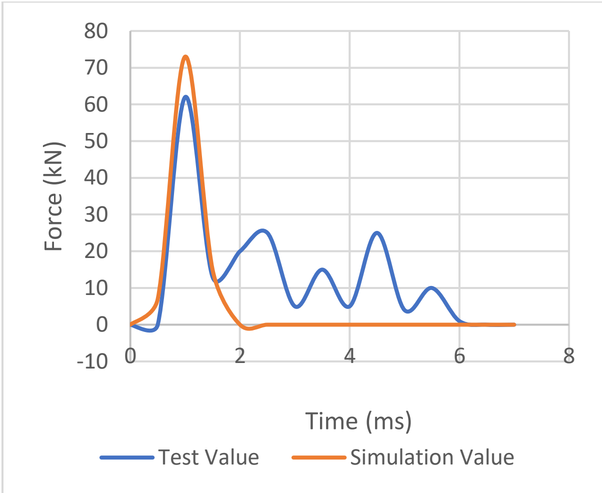
It is clearly observed that as the height of the drop increases, the peak impact force also increases. This is also the case of vertical stress and deflection with an increase in height. The damage of the specimen is the highest when impacted from a drop height of 2m.

5.5 Varying Reinforcement Ratio

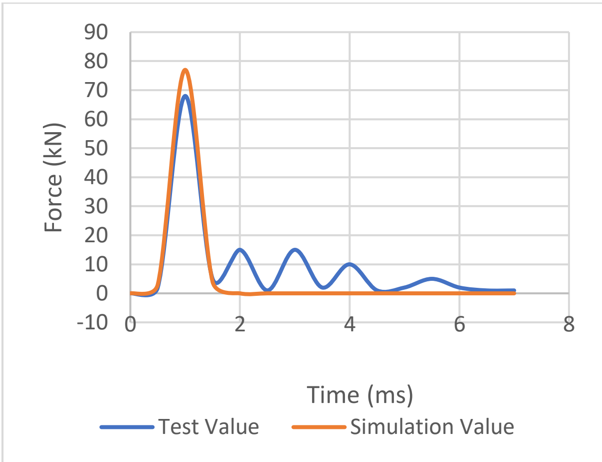
Reinforced GPC slabs of 100mm thickness and sides 500mm, were impacted using a drop weight of 5kg from a height of 1.5m with three different reinforcement ratios of 1.3%, 2.4%and 3.7%. The reinforcement ratio was changed using reinforcement bars of diameter 6mm, 8mm, and 10mm respectively. The reinforcement is arranged in 2 layers in both directions forming a two-layer mesh of HYSD 550 TMT bars as shown in the figures before. The dynamic response of the slabs under impact from each height was observed. The impact force-time history was plotted and the deflection-time history was also plotted. The simulation study was also conducted using Abaqus CAE software and the simulation and test results are compared.



(a)

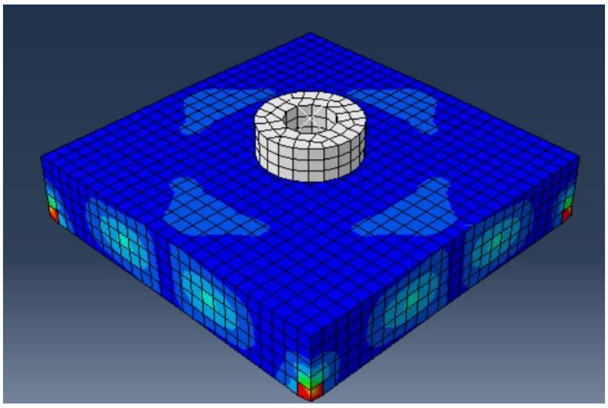


(b)

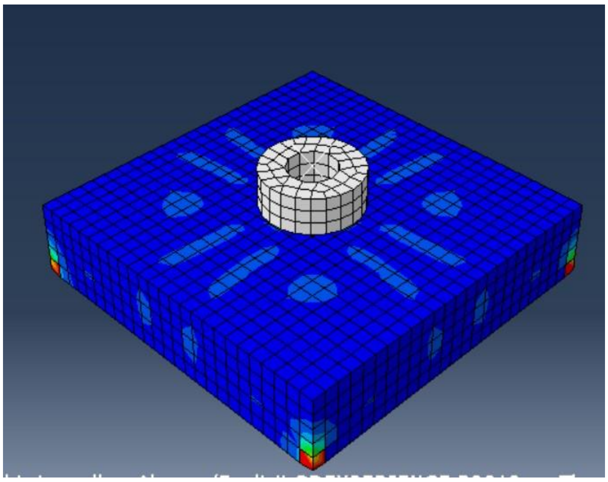


(c)

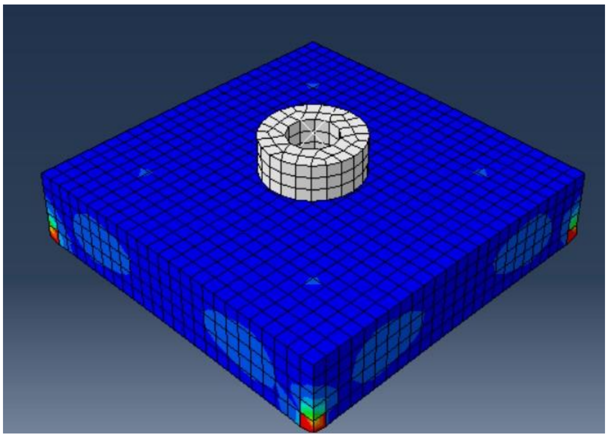
Fig 16:Comparison of impact force-time histories obtained from experiment and simulation study for a slab with reinforcement ratio of (a)1.3% (b) 2.4% (c) 3.7%.



(a)

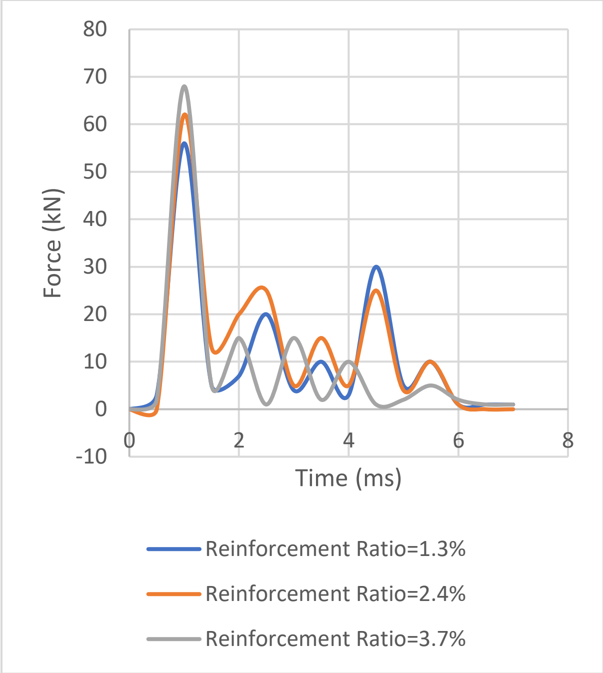


(b)

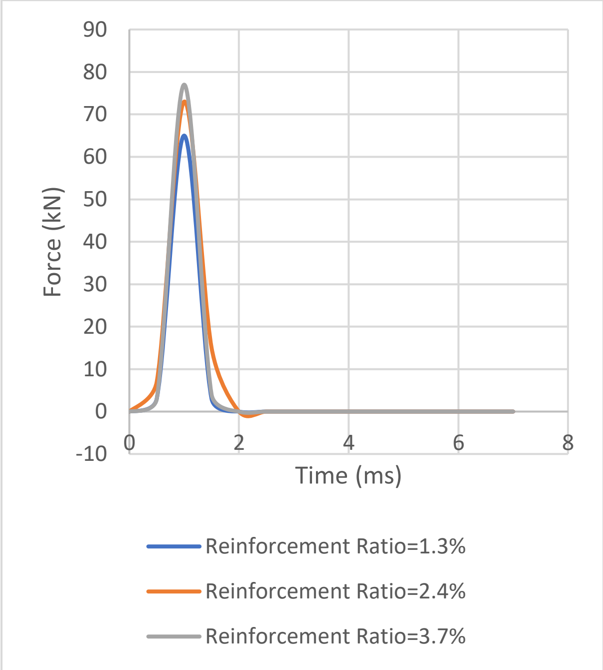


(c)

Fig 17: Stress distribution right after impact of reinforced GPC slab under an impact loading with a reinforcement ratio of (a)1.3% (b)2.4% (c) 3.7%



(a)



(b)

Fig 18: Comparison of impact force-time histories for different reinforcement ratios as obtained from (a) the experiment (b) the simulation

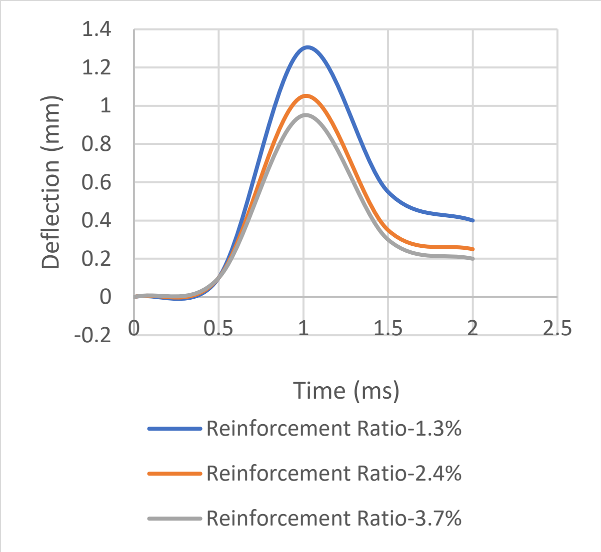
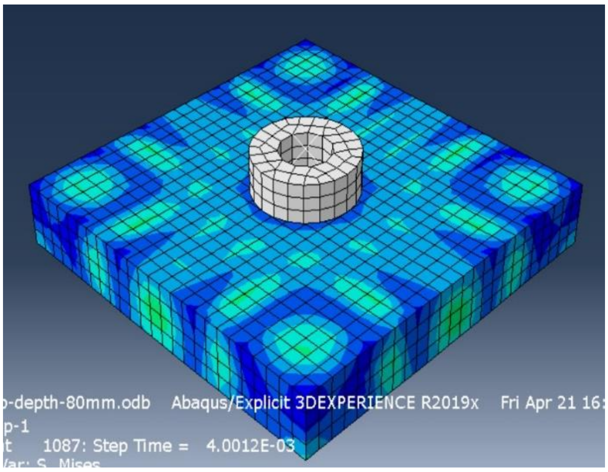


Fig 19:Comparison of displacement-time histories for different reinforcement ratios as obtained from the simulation

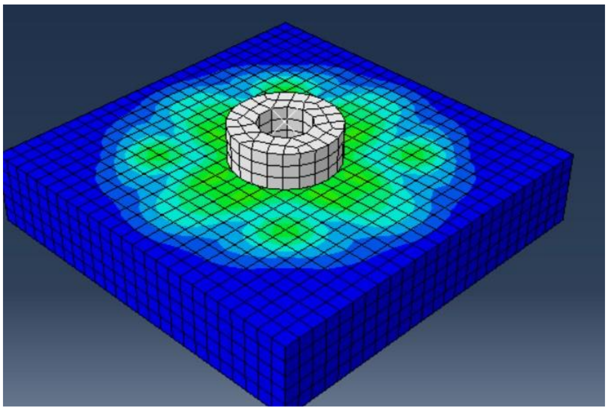
It was observed that, as the reinforcement ratio increases, the peak impact force also increases slightly. The vertical stresses also increase with the reinforcement ratio. However, the deflection of the slab decreased with an increase in the reinforcement ratio. Therefore, it can be concluded that increasing the reinforcement ratio in the range of 1.3%-3.7% improves the impact resistance of reinforced GPC slabs.

5.6 Varying Slab Depth

Reinforced GPC slabs of three different thicknesses 80mm,100mm, and 120mm having sides 500mm, were impacted using a drop weight of 5kg from a height of 1.5m with a reinforcement ratio of 2.4%. The reinforcement is arranged in 2 layers in both directions forming a two-layer mesh as in the above cases. In this parametric study, only the simulation study is conducted due to the limitation of time and resources and the experiment was not conducted. The impact force-time history was plotted and the deflection-time history was also plotted. The simulation study was conducted using Abaqus CAE software and the simulation and test results are compared.



(a)



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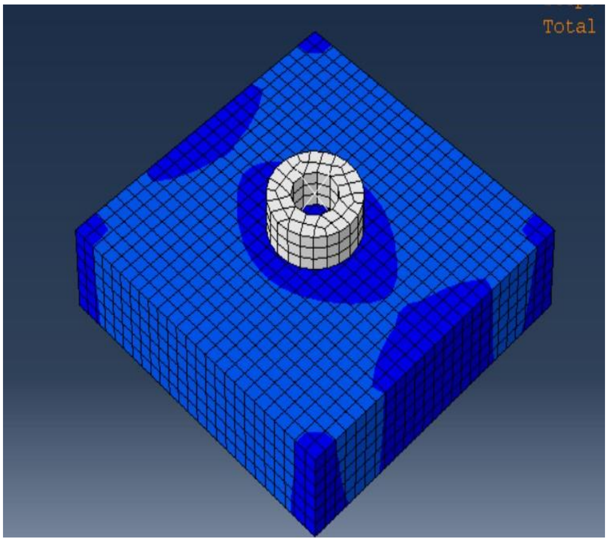


(c)

Fig 20: Stress distribution right after impact of reinforced GPC slab under an impact loading with a slab depth of (a)80mm (b)100mm (c) 120mm

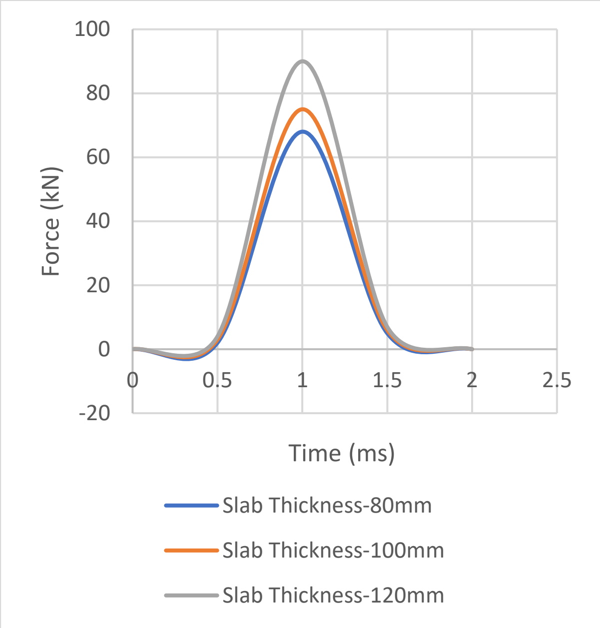


Fig 21: Comparison of impact force-time histories for different slab depths as obtained from the simulations

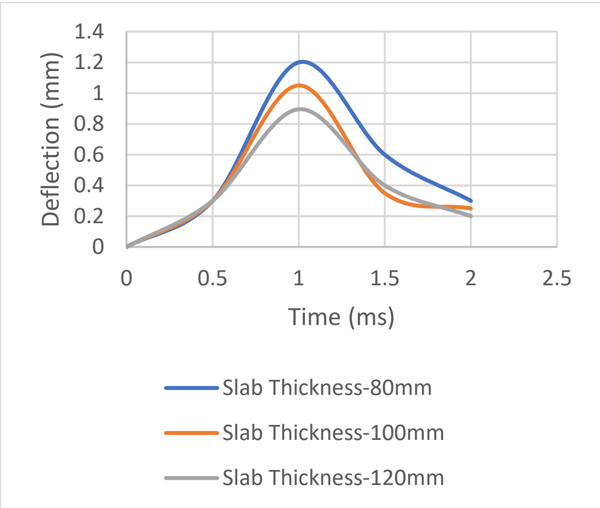
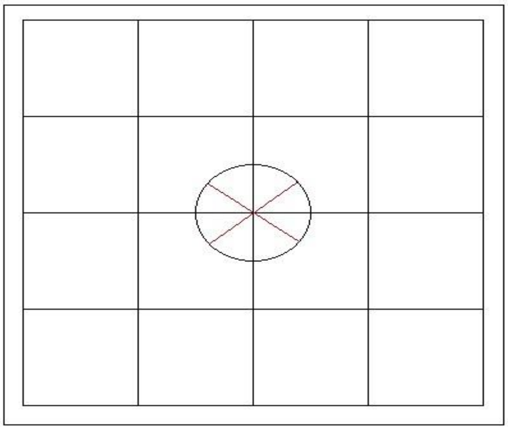


Fig 22: Comparison of displacement-time histories for different slab depths as obtained from the simulation

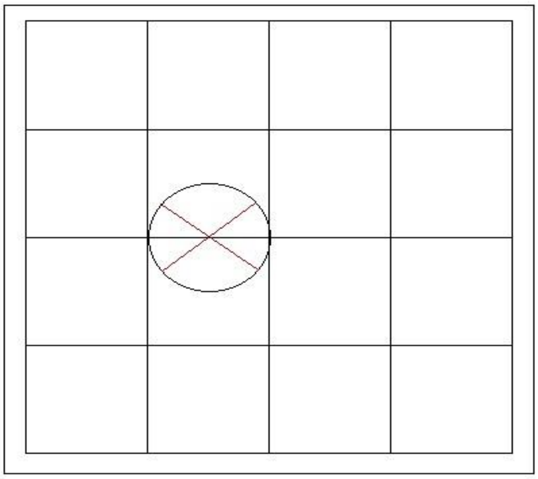
From the simulation study, it was observed that, as the depth of the slab increases, the peak impact force also increases, but deflection and damage decrease. Thus it means that we can improve the stiffness of the specimen by increasing the thickness of the specimen. Vertical impact compressive stresses increase proportionally with slab depth.

5.7 Varying Impact Location

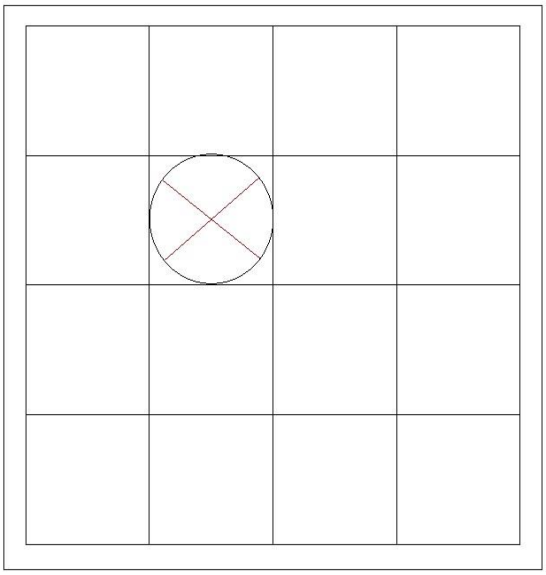
Reinforced GPC slabs with a depth of 100mm having sides of 500mm, were impacted using a drop weight of 5kg from a height of 1.5m with a reinforcement ratio of 2.4% at three different positions of impact location such as, over "single reinforcement," over "reinforcement intersection," and over "concrete at the reinforcement mesh," respectively. The reinforcement is arranged in 2 layers in both directions forming a two-layer mesh as in the above cases. In this parametric study, only the simulation study is conducted because in a real case, it is not possible to concentrate the entire force in a single point. The impact force-time history was plotted and the deflection-time history was also plotted. The simulation study was conducted using Abaqus CAE software and the simulation results are compared. The position of the impact location is shown in Figure 21.



(a)

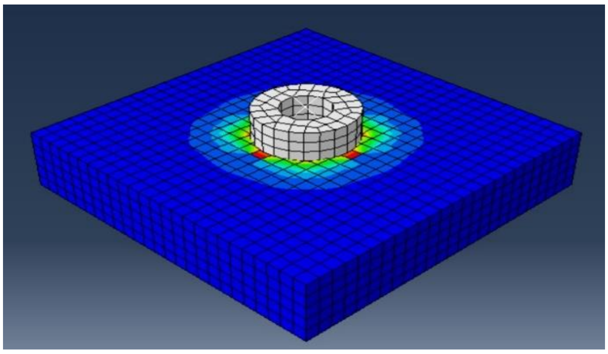


(b)

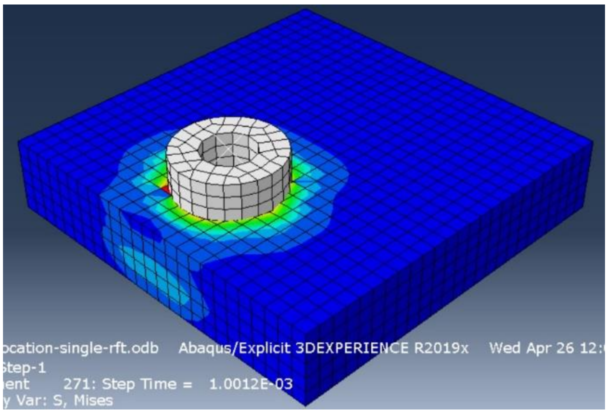


(c)

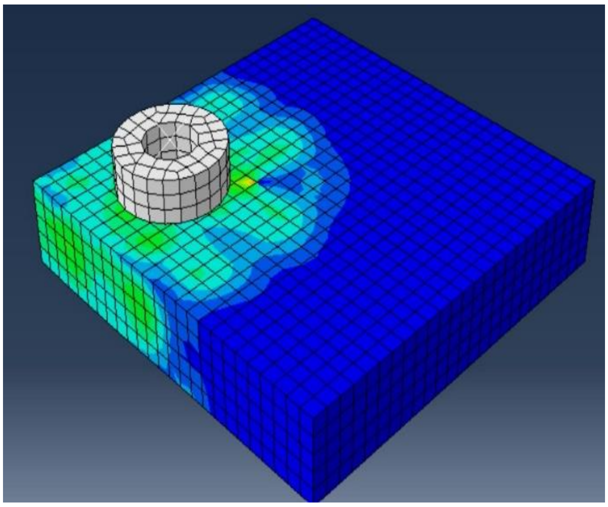
Fig 23: Position of impact locations of the slab (a) reinforcement intersection (b) single reinforcement (c) concrete at the reinforcement mesh



(a)



(b)



(c)

Fig 24: Stress distribution right after impact of reinforced GPC slab under an impact loading at locations (a)at reinforcement intersection (b) at single reinforcement (c) concrete at reinforcement mesh

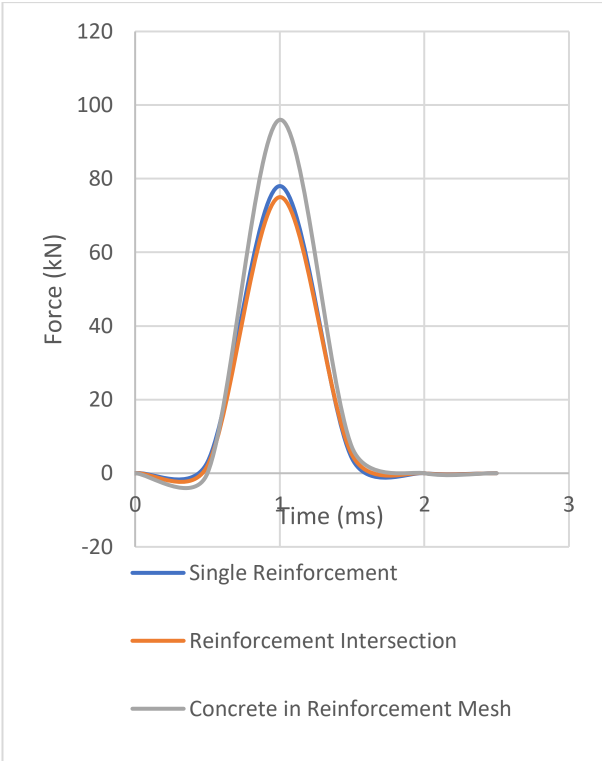


Fig 25: Comparison of impact force-time histories for different impact positions as obtained from the simulations

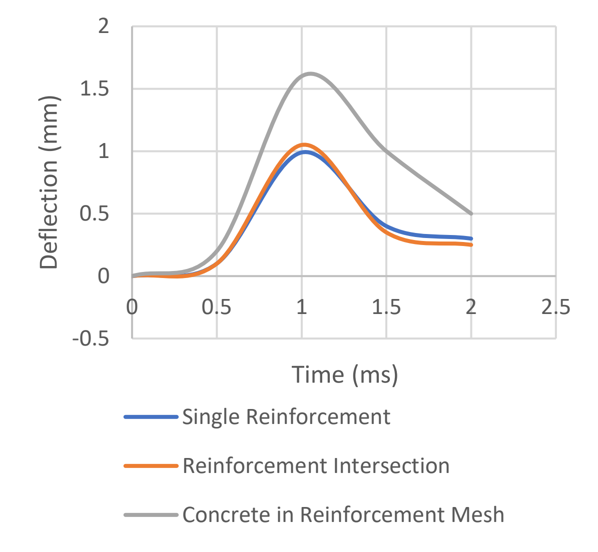


Fig 26: Comparison of displacement-time histories for different impact positions as obtained from the simulations

From the simulation study, it was observed that the peak impact force, deflection, and vertical stresses were highest when the impact was located on concrete at the reinforcement mesh. The impact force was least when impacted at the reinforcement intersection but the displacement was least when impacted on single reinforcement.

5.8 Time History of Impact Force

The impact force-time histories were plotted experimentally for, varying drop heights of 1m, 1.5m, and 2m, and for varying reinforcement ratios of 1.3%, 2.4%, and 3.7%. The impact force-time histories were plotted using numerical models, considering parameters: drop height (1m,1.5m, and 2m), reinforcement ratio (1.3%, 2.4%, and 3.7%), slab depth (80mm, 100mm, and 120mm) and location of impact (at reinforcement intersection, at single reinforcement and on concrete over reinforcement mesh). From the experiment, it was found that as the height of the drop of the impactor increased, the peak impact force also increased. For a drop height of 1m, the peak impact force recorded was 54kN, and for a drop height of 2m, the peak impact force was around 70kN. The slab showed more violent dynamic responses with increasing drop heights. In the case of increasing reinforcement ratio also, the impact force increased proportionally, with the lowest reinforcement ratio of 1.3% recording a peak impact force of 56kN and the highest reinforcement ratio showing a peak impact force of nearly 68kN. In the simulation study also, the peak impact force behaved similarly to that of the experiment output in the case of varying drop heights and reinforcement ratios. In both cases, the results obtained from FEA were more than that of experimental values. In case of varying slab depth and location of impact, the peak impact force increased with the depth of the slab, the highest slab depth showed the highest peak impact force of 90 kN and when the drop weight impacted at the location of concrete in the reinforcement mesh, the peak impact force was highest, nearly 95kN.

5.9 Deflection of GPC Slab Center

The deflection time history of slabs was plotted only from the simulation studies. The deflections varied from 0.85mm to 1.6mm in the case of geopolymer concrete slabs. Considering the variation of drop heights, the deflection was highest in the case of a 2m drop height and least in the case of a drop height of 1m. The deflection of the reinforced GPC slab reduced with the increase in reinforcement ratio. A similar trend was observed in the case of the depth of slabs as well. As the depth of the slab increased, the peak deflection of the slab decreased. Considering the location of impact, the slab showed a violent dynamic response when it was impacted on concrete in reinforcement mesh. The peak deflection of the slab was highest in this case. It is also notable that the deflection when impacted on single reinforcement was slightly less than the case of impact at reinforcement intersection. The slab was more stable when impacted at single reinforcement.

5.10 Surface Damage of GPC Slab

The surface damage of the specimen was observed for the experimental study. From this, it was observed that the slab impacted from a drop height of 2m showed the highest surface damage. It was observed that as the height of the impactor increases the surface damage also increased. As the reinforcement ratio increased, the crack distribution was almost similar, except the length of cracks reduced with the increase of reinforcement ratio. On further application of impact loads, more cracks were generated and they propagated from the center of the slab specimen to the corners. The cracks formed were small hairline cracks. But in case of impact from a drop height of 2m, the impactor made a small impression on the slab specimen. It could be concluded that the damage of the specimen increased significantly with the increase in the height of the drop.

4. CONCLUSION

The dynamic response of reinforced GPC slabs under impact loading has been studied experimentally and numerically, and the results are discussed in this research. Initial strength tests were performed on various geopolymer mixes to determine the most effective one. The combination that demonstrated the highest compressive and flexural strength (70% GGBS+20% Fly Ash +10% SF) has been selected for future investigation. Additionally, using numerical simulation, the effects of four parameters, namely impact point location, drop hammer height, reinforcement ratio, and slab thickness, on the dynamic response of the reinforced GPC slabs under impact loading are evaluated. The differences in dynamic response were also studied. The following observations were made from the study:

- The greenhouse gas emissions related to the production of concrete would be significantly reduced if geopolymer concrete were used instead of traditional Portland cement concrete. The cost and consumption of raw materials will also decrease as a result of the use of geopolymers.
- The compressive strength of the Geopolymer Mixes increased with increasing molarity of the NaOH solution and the highest compressive strength was exhibited by 16 Molarity set in all the four sets of Geopolymer Mixes tested.
- The flexural strength of the Geopolymer Mixes also increases with an increase in molarity.
- It was observed that workability significantly reduced with increasing molarity. The slump value was zero for all 16M mixes. Workability also reduced with increasing GGBS percentage.
- All GPC mixes showed better performance in terms of compressive strength, splitting tensile strength and flexural strength as compared to M30 mix conventional concrete.
- 70% GGBS + 20% FA + 10% SF mix with 16M NaOH solution (Na_2SiO_3/NaOH =2.5:1) showed the best performance in terms of compressive strength and flexural strength.
- 80% GGBS + 10% FA + 10% SF mix with 16M NaOH solution (Na_2SiO_3/NaOH =2.5:1) showed the best performance in terms of splitting tensile strength.
- Using GGBS and SF help to gain significant strength under ambient curing conditions, thus overcoming the major limitation of fly ash-based GPC, which is, the need for heat curing.
- The dynamic response of the reinforced GPC slab is relatively similar to that of the RC slab.
- The FEA results were higher than the test results.
- From the experiment, it was found that, as the drop height of the impactor increases, the impact force, as well as, the peak deflection and the maximum vertical stress also increase. This was supported by the simulation results as well.
- From the experiment, it was also found that, as the reinforcement ratio of the slab increases (1.3%,2.4%,3.7%), there is a slight reduction in peak deflection but the impact force and the vertical stresses increase slightly. The damage of the slab surface and the peak deflection were the least for the specimen with 3.7% reinforcement ratio This was supported by the simulation results as well. Thus, increasing the reinforcement ratio in the range (of 1.3%-3.7%) can improve the impact resistance of the slabs slightly.
- From the simulation study, it was found that when the point of impact is located on the concrete at the reinforcement mesh, the peak impact force, deflection, and vertical stress are larger than when impacting a single reinforcement and reinforcement intersection. Thus, the concrete at the reinforcement mesh of the RC slab is the weak area, and the dynamic response of the slab is stronger when it is impacted.
- From the simulation study, it was found that, as the depth of the slab increases, the impact force, as well as, the maximum vertical stress increases but, peak deflection decreases. The damage to the slab surface and the peak deflection was the least for slab with 120mm thickness. Thus, the impact resistance of the slab can be improved by increasing the slab thickness and thus the damage can be reduced. Also, the increase in impact energy intensifies the dynamic response of the slab.

- On further application of impact loads, cracks will be formed and they will continue to expand and new cracks will be generated.
- Structural-grade geopolymer concrete can be obtained when designed according to existing design codes- for the geopolymer mix considered in this study.
- GPC exhibits much higher mechanical performance than normal concrete.
- For GPC, higher strength can be obtained in lower design mixes.
- GPC can acquire high strengths under ambient curing conditions.
- GPC has the potential to replace conventional concrete in load bearing structural elements including slabs.
- GPC has the true potential to replace normal concrete, not only as a green alternative, but also with respect to its structural performance.

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