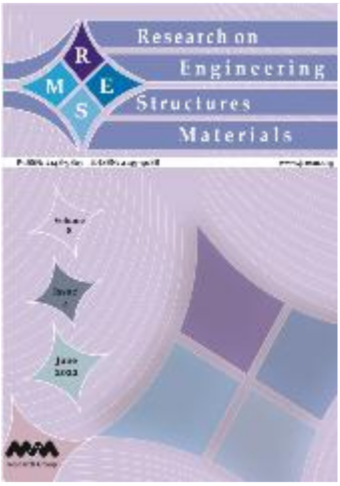
Research on Engineering Structures & Materials
journal homepage: http://www.jresm.org
Research Group



Optimization of high performance concrete composites by using nano materials

Naveen Arasu A, Natarajan Muthusamy, Balasundaram Natarajan, Parthasaarathi R

Online Publication Date: 20 March 2023
URL: http://www.jresm.org/archive/resm2022.602ma1213.html
DOI: http://dx.doi.org/10.17515/resm2022.602ma1213

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Arasu AN, Muthusamy N, Natarajan B, Parthasaarathi R. Optimization of high performance concrete composites by using nano materials. *Res. Eng. Struct. Mater.*, 2023; 9(3): 843-859.

Research on Engineering Structures & Materials
journal homepage: http://www.jresm.org
Research Group

Research Article

Optimization of high performance concrete composites by using nano materials

Naveen Arasu A*[1,a], Natarajan Muthusamy[1,b], Balasundaram Natarajan[1,c], Parthasaarathi R[2,d]

[1] *Dept. of Civil Eng., Karpagam Acedamy of Higher Education, Coimbatore, Tamilnadu, India*
[2]*Dept. of Civil Eng., Hindusthan College of Engineering and Technology, Coimbatore, Tamilnadu, India.*

Article Info

Article history:

Received 13 Dec 2022
Accepted 13 Mar 2023

Keywords:

Silica fume;
Fly ash;
Graphene oxide (GO)

Abstract

Investigating the mechanical properties of high-performance concrete (HPC) employing mineral admixtures including fly ash, silica fume, and graphene oxide was the primary goal of this investigation. The HPC utilised in this study was created using regular OPC fine and coarse aggregate, portable water, and mineral and chemical admixtures such as fly ash, silica fume, and graphene oxide at varied replacement levels, in addition to super plasticizer. In compliance with IS 10262:2019, which calls for the use of HPC mix grade M60 with a w/c ratio of 0.33, super plasticizer was added to the concrete to increase its workability. In order to evaluate different mixtures, cube and cylinder beam specimens with extra mechanical and durability features were all cast. Partial cement replacements of 0%, 5%, 10%, and 15% composed of fly ash and silica fume, graphite oxide with a concentration of 0.04 % were used in the casting of M1 through M4, respectively. The concrete's mechanical behaviour, which was measured in terms of compressive strength, was then put to the test seven, fourteen, and 28 days after it was cast. The results of the tests demonstrate that including mineral admixtures usually improves the combinations' mechanical and durability attributes.

1. Introduction

Due to its excellent workability, high density, high elastic modulus, and high dimensional stability with strong abrasion and impact resistance, high soundness, and cavitation resistance, High Performance Concrete (HPC) is currently utilized extensively across the world. As a result of its toughness and protection from salt probing, HPC is sometimes referred to as "durable" concrete since it outlives conventional concrete by a significant margin. The standard components of water, Portland cement, fine and coarse aggregates, and admixtures are included in this designed concrete, which also contains the classic ingredients. ACI's definition of high-performance concrete states that it "meets unusual combinations of performance and uniformity requirements that cannot always be routinely attained with conventional components and standard mixing, placing, and curing techniques."

HPC is incredibly well-known for achieving financial benefits through environmentally friendly construction methods. There is only one option to lessen the impact of an external chemical assault on concrete, and that is to decrease the concrete's porosity and permeability in order to lessen or at least moderately slow down the penetration of the aggressive chemicals. When typical concrete is subjected to compressive stresses, failure might take place either inside the hydrated cement paste itself or along the interface

---

*Corresponding author: naveenanbu07@gmail.com
[a] orcid.org/0000-0002-5708-0086; [b] orcid.org/0000-0001-8226-8307; [c] orcid.org/0000-0002-4831-1209; [d] orcid.org/0000-0001-9614-0769

DOI: http://dx.doi.org/10.17515/resm2022.602ma1213

between the cement paste and aggregate particles. Normal concrete has a weak spot at this interface, which is referred to as the transition zone.

A change in the microstructure of the concrete composite, namely a reduction in the thickness, related voids, and micro cracks, as well as a more uniform distribution of the particles in the transition zone, is what accounts for the improved attributes of high-performance concrete. Utilizing both chemical and mineral admixtures, such changes in microstructure are accomplished. In order to make HPC, a significant decrease in the amount of mixing water is required. Concrete that has a lower w/c ratio will be more durable. In order to obtain the high levels of reactivity, silica fume, an additive made from a low-calcium aluminium silicate mineral, has its particle size distribution carefully managed. The ultrafine particles' fineness and strong reactivity contribute to a more effective hydration process. Silica fume addition enhances the particle packing of paste ingredients, which is correlated in concrete with increased strength and life span of concrete. To create more cementitious components and hence boost long-term strength, fly ash grain reacts with free lime in the cementious components.

Fly ash will diminish the amount of water entering into the concrete by diminishing the w/c ratio and, consequently, the quantity of capillary pores in the mass. As a result, less water is required. The high specific area, however, increases the requirement for water. The combined effect of these two results in a net increase in water consumption when compared to standard-strength concrete for a given degree of workability.

Water usage is decreased by using a super plasticizer. By deflocculating the cement lump, producing cement water mixes, as well as dispersion systems, water lowering admixtures, and super plasticizers, provide the optimal conditions for full hydration of cement. The likelihood of anhydrous cement grains being present in the concrete structure is decreased, and the pore structure is enhanced by bringing almost all cement particles into complete contact with water during the hydration process. Superplasticizers may be able to cut back on water consumption by about 30%.

2. Literature Review

By incorporating nano particles into cementitious composites, fibres have been shown to regulate nano and microscale fractures in the early stages, improving the quality of cement-based composites. (12). Consider graphene oxide nano alumina carbon nano tubes as an example of a reinforced material in cementitious composite structures. (4)

The impact of GO on enriching the cementitious materials' microstructure had a favourable effect on speeding up the hydration process. (7). The mechanical strength, thus, saw a substantial improvement. By adding GO, the moisture transport in the cementitious matrix was successfully constrained. GO successfully prevented the intrusion of chlorides into the cementitious matrix as a result. (1,15)

Among the brodies approach, the staudenmaier method and the hummer and offeman method, the hummer and offeman method is the most commonly utilised in the production of graphene oxide. The pros and cons of the three ways the brodies synthesis process was explored, and it was discovered that the brodies approach produces the cleanest and most stable graphene oxide samples. (2)

The workability of new concrete is the most important factor in influencing its uniform mixing, ease of transport, placement and compaction. The addition of extra components to concrete causes it to lose its workability. Worse, adding nanoparticles to the cementitious matrix alters the rheological properties of cement pastes, making cement mortar and concrete mixes considerably more difficult to work with. (8). This might be due to a decrease in free water, which is needed for lubrication at a certain water-to-cement ratio w/c to moisten the nanomaterial's increased surface area. (6). Superplasticizers were provided to the fresh mix in order to keep it flowing. Superplasticizers based on polycarboxylate ethers have been discovered to be an efficient additive for sustaining cementitious matrix workability. (3)

In a minor slump test, the slump diameter was decreased by 41.7 percent when compared to the reference sample at a GO dose of 0.05 percent, and there was a 34.6 percent drop in slump. A 0.2 percent polycarboxylate superplasticizer added to the cementitious matrix increased flow by 34%, indicating that it is an important additive for preserving the workability of new mixes by reducing water consumption.(9)

The researchers studied the influence of graphene oxide nanosheets on compressive tensile and flexural strength tests using dosages of 0.01 percent, 0.02 percent, 0.03 percent, and 0.05 percent by weight of cement. In a cement composite made up of 165 g of water, 450 g of cement, 1350 g of normal sand, and a trace of graphene oxide, 0.9 g of polycarboxylate superplasticizer was utilised. The graphene oxide nanosheets are 8 nm thick and range in size from 80 to 260 nm. They are 8 nm thick and contain 29.75 percent oxygen. (11)

For 28, 56, and 90 days of cure, the initial surface absorption and sorptivity tend to decline as GO content rises. The non-destructive method's (UPV) findings demonstrated that the homogeneity of the GO reinforced concrete composite remained unaltered as GO concentration increased, and that the mix made with 0.08% had the highest average velocity across all curing ages when compared to the control mix and the other mixes. (10,16)

It’s possible that the improved performance of GO cement-based composites is due to GO dispersion in the cementitious matrix. Thus, the process for efficient GO mixing is critical in increasing the performance of cementious composites, and further research is needed in this area in concrete since excessive GO sheet dosage has a negative impact on performance. (13, 14). Many studies on the microstructure of GO cementious composites found a significant improvement in the pore structure reduction in porosity and filler effect of GO in cement pastes and cement mortars, but more research is needed before GO can be widely used in concrete. (5) Previous studies on the durability of GO-incorporated cementious composites found that they were resistant to the freeze-thaw phenomenon, indicating that more study into the durability qualities of cement-based materials is needed.

Slump values decrease almost linearly with increase in silica fume content. The increase in replacement level of cement with silica fume there is an increase in compressive strength up to 20% when compared with conventional concrete. [17] By the usage of silica fume and flya sh in concrete will reduce the land pollution and helps in recycling of waste materials [18].

Particularly in the mixtures having high foam content, silica fume introduction resulted in superior compressive strength values and greater compressive strength/thermal conductivity ratios than fly ash introduction. [19] Based on the analysis of the results of microstructural tests and the evaluation of the propagation of macroscopic cracks, it was established that along with the substitution of the cement binder with the combination of mineral additives, the composition of the cement matrix in these composites changes, which implies a different, i.e., quasi-plastic, behavior in the process of damage and destruction of the material. [20]

The effect of F/S ratio depended strongly on the curing condition. Under ambient curing, the optimum F/S ratio of 90/10 was observed. For accelerated curing, the addition of silica fume provided negative effect on the mechanical properties. The optimum F/S ratio was observed in mix without silica fume.[21] The best compressive strength was attained by the mix containing 80% FCA and 20% GGBFS, and hence could be implemented for normal construction works [22]

3. Material Properties

3.1. Cement

All of the specimens were cast using Portland pozzolana cement 53 grade conformities to IS 12269-1987 and with a relative density of 3.15. Cement has been tested for fineness using a sieve analysis with a 90-micron sieve, specific gravity with le-chatliers equipment, and ultimate setting time using a vicat device. The ultra-modern OPC 53 grade cement that was used was procured from Ariyalur. Table 1 shows the properties of cement.

Table 1. Properties of cement

Tests on cement	Results
Specific gravity test	3.15
Fineness test (m2/Kg)	274
Consistency test (%)	25.0
Initial setting time (min)	135
Final setting time (min)	290
Strength test (N/mm2)	38.26 48.30 61.80
Soundness test (mm)	1.2

3.2. Fine Aggregate

Fine aggregate was taken from Karanempettai and confirmed to be M-sand according to IS 383-1970. Its sp. gr. is 2.860. Tests on fine aggregate include grading and sp. gr. using a pycnometer to measure fineness ratio. Table 2 shows the properties of fine aggregate.

3.3. Course Aggregate

Crushed angular granite stone confirming to a size of 12.5mm and 20mm confirming to table 7 of IS 383: 1970 was used, having a sp. gr for 12.5 mm is 2.87 and for 20mm is 2.82. Coarse aggregate was obtained from Karanempettai. Table 3 shows the properties of course aggregate.

3.4. Silica Fume

Having a low calcium aluminium silicate grading reactivity, silica fume is a mineral-based additive. The hydration process is brought on by the enhanced reactivity and grading of SF. When SF is used to increase the particle packing of paste components, the resulting concrete is stronger and also possesses a longer life span.

The manufacturer of silica fume is called Silica fume & Admixtures Pvt. Ltd., and is located in Nagpur, Maharashtra. 2.71 is the specific gravity. Table 4 shows the properties of silica fume.

3.5. Fly Ash

Fly ash is a thin grey powder that is a byproduct of combustion power plants and is mostly made up of spherical glassy particles. When pulverised coal is burned, a finely divided residue called fly ash is produced, which is used in combustion power plants.

In Metturs (MTPP), collected fly ash has a specific gravity of 2.13. Table 5 shows the properties of fly ash.

Table 2. Properties of fine aggregate

Tests on fine aggregate	Results
Sieve analysis (Fineness modulus) (m^2/Kg)	2.85
Density	
Loose (Kg/m^3)	1683.00
Rodded (Kg/m^3)	1780.00
Specific gravity	2.860
Water absorption (%)	1.06

Table 3. Properties of course aggregate

Tests on Coarse Aggregate	Results (12.5mm)	Results (20mm)
Density		
Loose (Kg/m^3)	1736	1680
Rodded (Kg/m^3)	1786	1777
Specific gravity	2.82	2.87
Water absorption (%)	0.23	0.24
Flakiness index (%)	10.6	7.2
Elongation index (%)	11.20	13.6

Table 4. Properties of silica fume

Tests on Silica Fume	Results
Fineness (m^2/Kg)	2730
Particle size range	
D_{50} (μm)	3.85
(b) D_{95} (μm)	8.79
Slag Activity Index	
7 days	87.20%
28 days	110%

Table 5. properties of fly ash

Test on Fly ash	Results
Bulk density (gm/cc)	0.9-1.3
Specific gravity	1.6-2.6
Plasticity	Lower or non-plastic
Shrinkage limit (vol stability)	Higher
Free swell index	Very low
Porosity (per cent)	30-65
Surface area (m^2/kg)	500-5000
Lime reactivity (MPa)	1-8

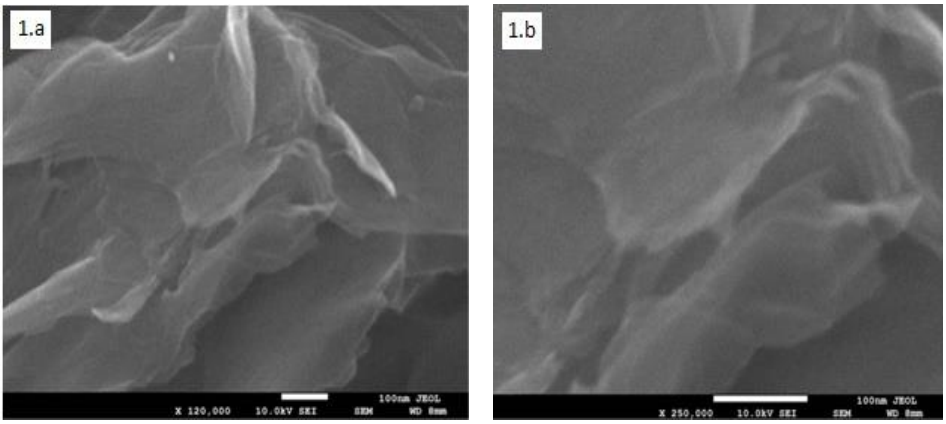
3.6. Graphene Oxide

Chemical admixtures like graphene oxide are used to improve the durability and strength of concrete.

The Karnataka-based Ad-nano technologies company produces grapheme oxide. Table 6 shows the properties of graphene oxide. Figure 1 (a & b), 2 and 3 shows the GO FE SEM images and GO FTIR image shows the variations of wane number and transmittance.

Table 6. Properties of GO

GO	Value
Elastic modulus	23.42
Elongation at break	0.6%
Electrical conductivity	Non conductive
Dispensability in water	Highly dispersible



(a) (b)

Fig. 1 (a) and (b) GO FE SEM

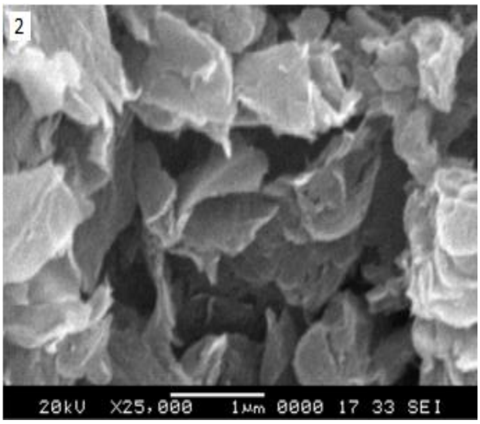


Fig. 2 GO SEM

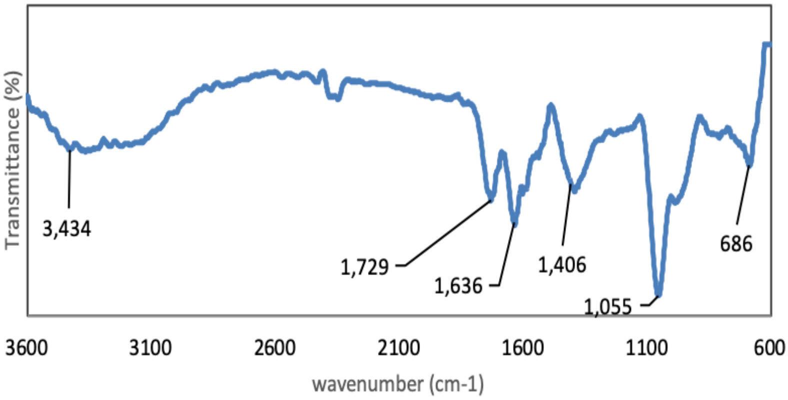


Fig. 3 GO FTIR

3.7. Super Plasticizer

In order to improve the flow ability of concrete, a chemical additive called CAC Hyperfluid plus (H5), which is readily accessible, was utilized.

A concrete super plasticizer called CAC-HYPERFLUID PLUS (H5), which is based on polycarboxylic ether, is used to decrease the amount of water in admixed concrete as well as to make it easier to work with. In order to provide substantial water reductions of up to 40% without sacrificing flow ability or to manufacture high-quality concrete with decreased permeability, CAC-HYPERFLUID PLUS (H5) has been particularly designed. Table 7 shows the properties of superplasticizer.

Hydrostatic pressure from one side to a concrete specimen with known dimensions that is inside a specially designated cell, and measuring the amount of water that percolates through the specimen in a certain amount of time through the other end of the specimen. The permeability is inversely correlated with the amount of water collected. For a full day, the test pressure was maintained. This shows the lowering concrete's water permeability, improving the material's resilience.

4. Mix Proportions and Casting

The mix proportioning for a concrete of M60 grade concrete using Fly ash, Silica Fume and Graphene oxide is given below in the table 8 various mix.

Table 7. Properties of super plasticizer

Property	Result
Appearance	Brown free flowing liquid
Base material	Modified poly-carboxylic ether
Specific gravity at 25o C	1.080+/- 0.020
Chloride content	Maximum 0.2%
pH	Minimum 6

Table 8. Quantity of materials used in kg/m^3

Mix	Description	Cement (Kgs.)	GO (Gms)	Fly ash (Kgs.)	SF (Kgs.)	Water (Kgs.)	FA (Kgs.)	CA (Kgs.)	SP (Lits)
M1	Conventional	470	0.00	0	0	141	659	1324	4.70
M2	% GO + 5% Fly ash + 5 % Silica Fume	422.81	0.19	23.5	23.5	141	659	1324	4.70
M3	% GO + 10 % Fly ash + 10 % Silica Fume	375.81	0.19	47.0	47.0	141	659	1324	4.70
M4	0.04 % GO + 15% Fly ash + 15 % Silica Fume	328.81	0.19	70.5	70.5	141	659	1324	4.70

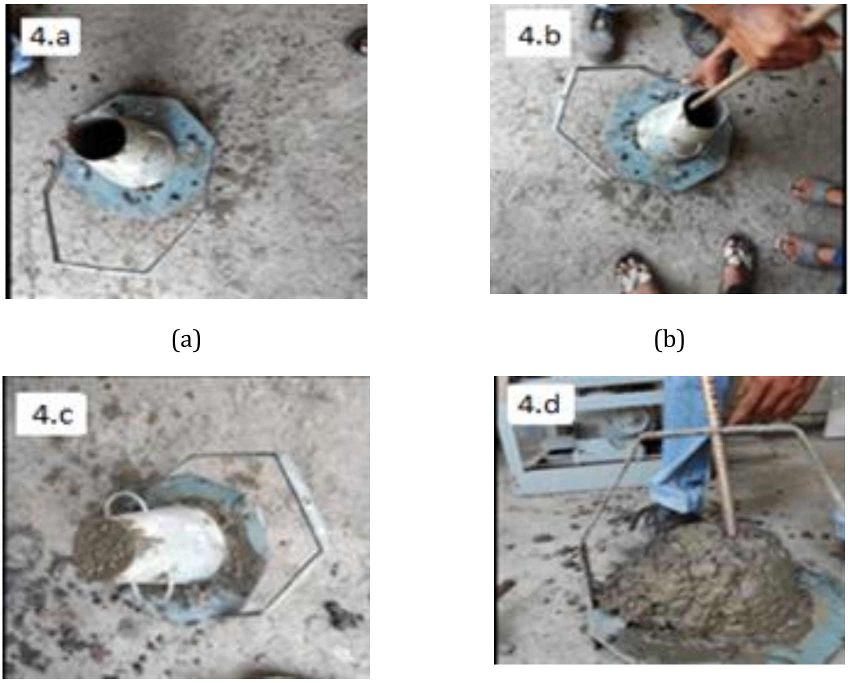
5. Test Method

5.1. Fluidity Test

Slump cone tests and compaction factor tests are conducted to determine the fluidity of fresh concrete. The test results are given below in table 9. Figure 4 (a, b, c & d) shows slump test. Figure 5 and 6 shows how slump value and compaction factor decrease with increase in fly ash, silica fume and graphene oxide with various mix.

Table 9. Slump value and compaction factor

Mix	Description	Slump Value (mm)	Compaction Factor
M1	Conventional	110	0.904
M2	0.04% GO + 5% Fly ash + 5 % Silica Fume	105	0.900
M3	0.04% GO + 10 % Fly ash + 10% Silica Fume	99	0.895
M4	0.04 % GO + 15% Fly ash + 15% Silica Fume	93	0.890



(a) (b)

(c) (d)

Fig. 4 Slump test

5.2. Strength Test

Compressive, Split tensile, and flexural tests were conducted to find the physical properties of concrete and the results are given below in tables 10, 11, and 12. Figure 7 (a, b, c & d), 9 (a & b) and 11 shows the image of compression test on cube of various mixes, the compressive strength increases in mix M1, M2 and M3 and reduces in M4 mix for cylinder and beam. Figure 8, 10 and 12 shows the variation of compressive and split tensile strength increase with addition in percentage of fly ash, silica fume and graphene oxide for various mix.

The compressive strength of the hardened concrete cubes of size 150mm x 150mm x 150mm was found using the compression testing machine of capacity 200kN. The tests were carried out at a uniform rate of 14N/mm²/min after the specimen had been centered in the testing machine.

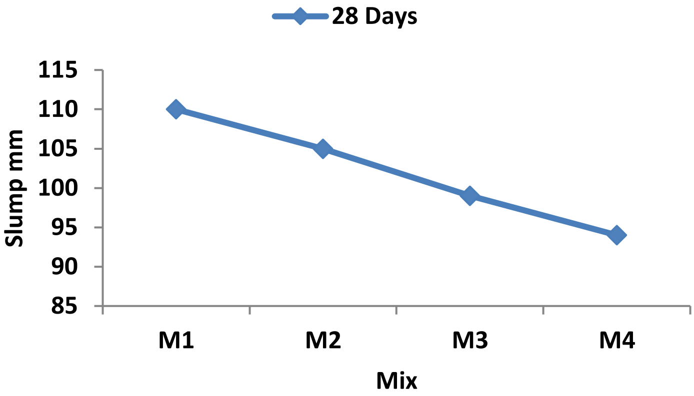


Fig. 5 Slump value

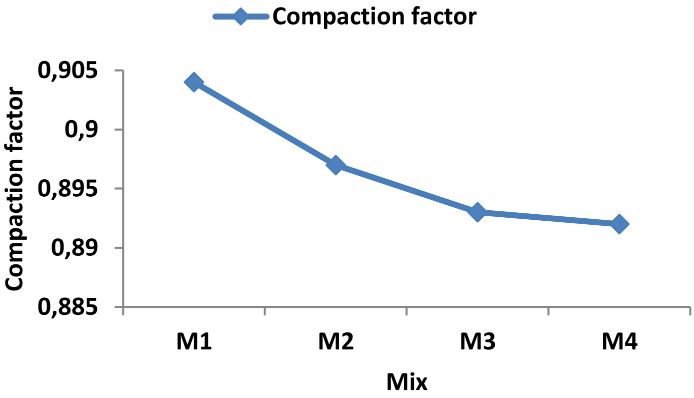
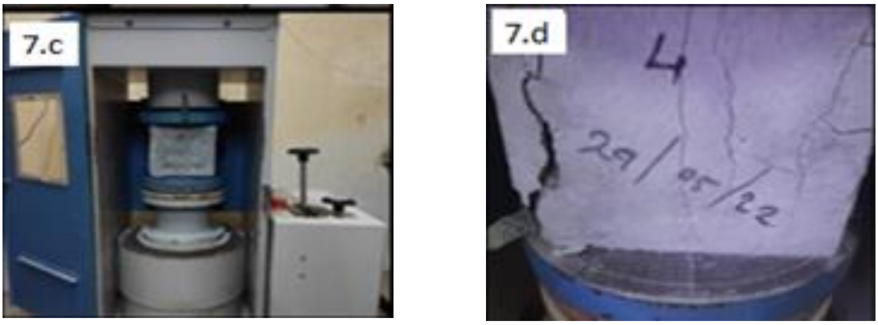


Fig. 6 Compaction factor

(a)

(b)



(c) (d)

Fig. 7 Compression test

Table 10. Compressive Strength

Mix Proportion	7 Days N/mm^2	14 Days N/mm^2	28 Days N/mm^2
M1	40.02	47.82	66.31
M2	57.04	61.83	74.88
M3	62.68	67.44	82.15
M4	38	49.68	76.33

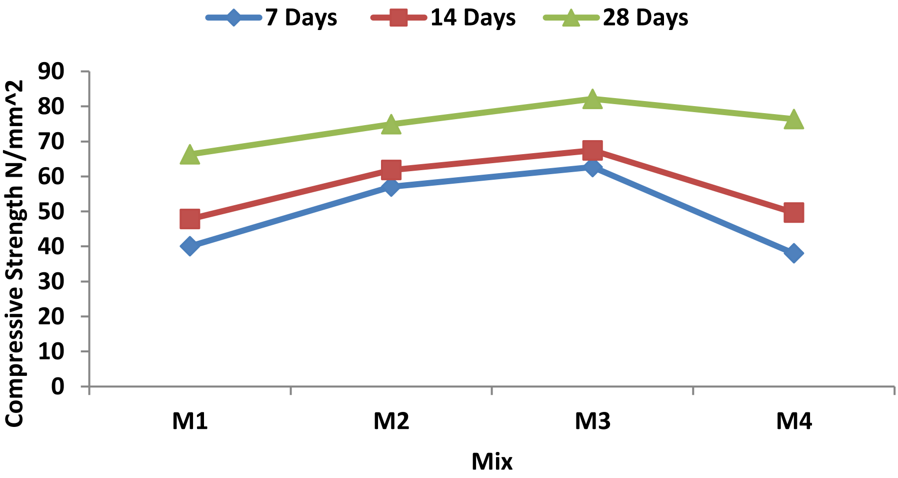
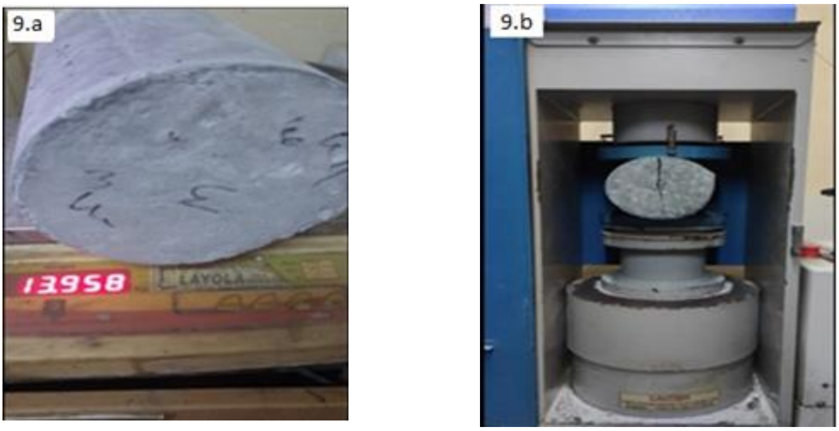


Fig 8. Compressive strength

Table 11. Split tensile strength

Mix Proportion	7 Days N/mm^2	14 Days N/mm^2	28 Days N/mm^2
M1	4.60	4.96	5.04
M2	4.68	5.13	5.32
M3	5.08	5.41	5.83
M4	5.02	5.33	5.67



(a) (b)

Fig. 9 Split tensile test

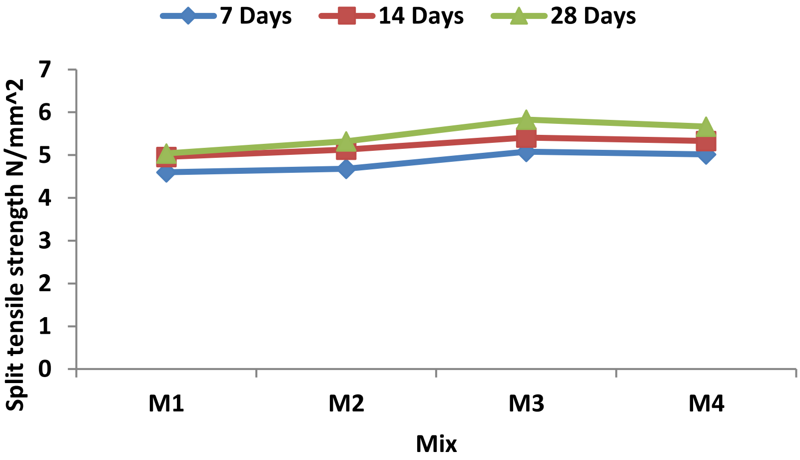


Fig 10. Split tensile strength

Table 12. Flexural test

Mix Proportion	28 Days N/mm^2
M1	6.79
M2	7.32
M3	7.81
M4	7.63

Fig. 11 Flexural test on beam

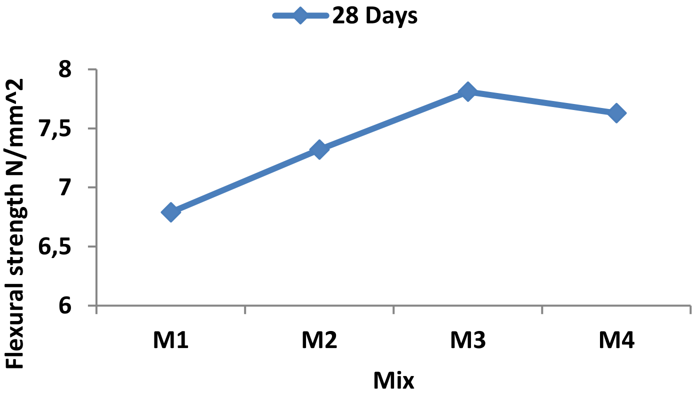


Fig. 12 Flexural strength

5.3. Test for Permeability

The equation, which is provided in the code, was used to compute the coefficient of permeability during permeability tests that were carried out in accordance with IS 3085-1965.

The device comprises a reservoir that is connected to the cell via a metal pipe that is 500 millimetres long and 50 to 100 millimetres in diameter. The permeability cell measures

115 mm in height and 115 mm in diameter. A scale has been installed in the reservoir. The permeability cell is equipped with the necessary valves for admitting water, compressed air, and water drainage. The permeability cell assembly is coupled to a 5 hp air compressor to maintain a pressure between 5 and 15 kg/cm^2. To remove all laitance, the specimen was extensively cleaned with a hard wire brush. Water that was clean and in sufficient supply was made available for the permeability test. This investigation has been conducted at a pressure of 5 kg/cm^2. The test involves applying a known hydrostatic pressure from one side to a concrete specimen with known dimensions that is inside a specially designated cell, and measuring the amount of water that percolates through the specimen in a certain amount of time through the other end of the specimen. The permeability is inversely correlated with the amount of water collected. For a full day, the test pressure was maintained.

Table 13. Permeability test

Mix Proportion	Permeability 10^{-9} cm/sec
M1	0.48
M2	0.46
M3	0.43
M4	0.38

5.4 Microstructural Observation

To compare the structural cytology of the fly ash, silica fume and GO concrete composites and conventional mix, scanning electron microscopy was used. In mixes made with fly ash, silica fume and GO, huge hydrated crystals, calcium silicate hydrates (C-S-H), were seen in contrast to the presence of ettringites, pointed crystals, and holes in the control mix as seen on the SEM micrograph. The hydrated crystals in Fig. 13 prevented pore capillaries from forming, making the concrete less porous and increasing its strength and endurance. Fig. 14. Represents the SEM pictures of 0.04% GO and 10% silica fume and 10% fly ash with 90 day old concrete.

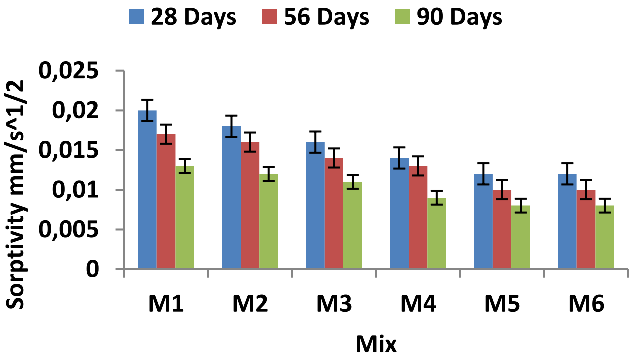


Fig. 13 Sorptivity of all the mixes at 28, 56 and 90 days curing age

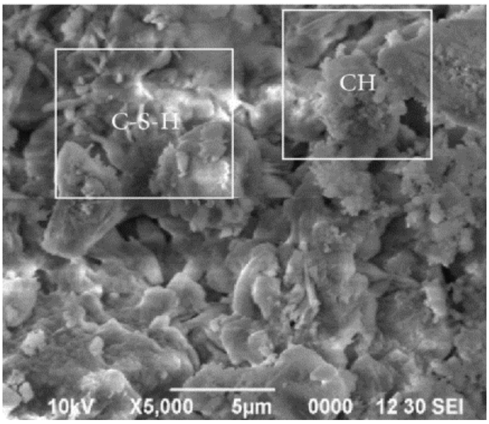


Fig. 14 SEM of mix GO 0.04%

6. Conclusion

In the previous study they have optimized only the graphene oxide. The present study concluded that how fly ash, silica fume, and graphene oxide can be made possible and how they performed when used in place of certain cements to create high-performance concrete. For a water-binder ratio of 0.30, silica fume is place of cement in the following percentages: 0%, 5%, 10%, and 15% for fly ash is place of cement in the following percentages: 0%, 5%, 10%, and 15% and for graphene oxide dispersion is added to cement by 0.04% percentage.

The workability of the fresh concrete reduces the by adding silica fume, fly ash and graphene oxide to counteract the reduction of workability super plasticizer is added. The super plasticizer called CAC-HYPERFLUID PLUS (H5), which is based on polycarboxylic ether, is used to enrich the flow ability property of concrete.

- The findings of this research show that optimization for the M60 grade of concrete by replacing 10% of silica fume, 10% of fly ash, and 0.04% of graphene oxide for cement in concrete shows better results when compared to all the mix including the conventional concrete.
- Due to increase in fly ash and silica fume in concrete it reduces the workability of fresh concrete due to that after M3 mix the strength also reduces.
- There is an appreciable increase in compressive strength of about 24 percentage, split tensile strength of about 16 percentage, and flexural strength of about 15 percentage while maintaining other mix design parameters at their original levels.
- Due to improved permeability of concrete for about 26 percentage, the durability of concrete also increases. And with increasing curing age the value decreases drastically indicating the improvement of porosity at the micro-level of the concrete.
- The size of the hydrated crystals grows as the proportion of GO content does, showing that GO nano materials are filling the pores. The hydrated crystals prevents the pore capillaries from forming, making the concrete less porous and increasing its strength and endurance.
- Fly ash, silica fume, and GO were incorporated into the concrete to reinforce it and improve its mechanical and durability properties. These might be the best option among the various nanomaterials in the near future for building stronger, better robust, and longer-lasting concrete.

References

[1] Mohammed A, Al-Saadi NTK, Sanjayan J. Inclusion of graphene oxide in cementitious composites: state-of-the-art review. Australian Journal of Civil Engineering. 2018; 1-15. https://doi.org/10.1080/14488353.2018.1450699

[2] Gong K, Pan Z, Korayem AH, Qiu L, Li D, Collins FG, Wang CM, Duan W. Reinforcing effects of graphene oxide on Portland cement paste. Journal of Materials in Civil Engineering. 2015; 27: 1-6. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001125

[3] Wille K, Loh KJ. Nanoengineering ultra-high-performance concrete with multiwalled carbon nanotubes. Transportation Research Record. 2010; 2142: 1,: 119-126. https://doi.org/10.3141/2142-18

[4] Sanchez F, Sobolev K. Nanotechnology in concrete-a review. Construction Building Materials. 2010; 24: 11: 2060-2071. https://doi.org/10.1016/j.conbuildmat.2010.03.014

[5] Peng H, Ge Y, Cai CS, Zhang Y, Liu Z. Mechanical properties and microstructure of graphene oxide cement-based composites. Construction Building Materials. 2019; 194: 102-109. https://doi.org/10.1016/j.conbuildmat.2018.10.234

[6] Senff L, Hotza D, Lucas S, Ferreira VM, Labrincha JA. Effect of nano-SiO2 and nano-TiO2 addition on the rheological behavior and the hardened properties of cement mortars. Materials Science Engineering A. 2012; 532: 354-361. https://doi.org/10.1016/j.msea.2011.10.102

[7] Zhao L, Guo X, Liu Y, Zhao Y, Chen Z, Zhang Y, Guo L, Shu X, Liu J. Hydration kinetics, pore structure, 3D network calcium silicate hydrate, and mechanical behavior of graphene oxide reinforced cement composites. Construction Building Materials. 2018; 190: 150-163. https://doi.org/10.1016/j.conbuildmat.2018.09.105

[8] Mokhtar MM, Abo-El-Enein SA, Hassaan MY, Morsy MS, Khalil MH. Mechanical performance, pore structure and micro-structural characteristics of graphene oxide nano platelets reinforced cement. Construction Building Materials. 2017; 138: 333-339. https://doi.org/10.1016/j.conbuildmat.2017.02.021

[9] Birenboim M, Nadiv R, Alatawna A, Buzaglo M, Schahar G, Lee J, Kim G, Peled A, Regev O. Reinforcement and workability aspects of graphene-oxide reinforced cement nanocomposites. Composites B Engineering. 2019; 161: 68-76. https://doi.org/10.1016/j.compositesb.2018.10.030

[10] Devi SC, Khan RA. Effect of graphene oxide on mechanical and durability performance of concrete. Journal of Building Engineering. 2020; 27: 1-12. https://doi.org/10.1016/j.jobe.2019.101007

[11] Lv S, Ma Y, Qiu C, Sun T, Liu J, Zhou Q. Effect of graphene oxide nanosheets of microstructure and mechanical properties of cement composites. Construction Building Materials. 2013; 49: 121-127. https://doi.org/10.1016/j.conbuildmat.2013.08.022

[12] Sharma S, Kothiyal NC. Influence of graphene oxide as dispersed phase in cement mortar matrix in defining the crystal patterns of cement hydrates and its effect on mechanical, microstructural and crystallization properties. RSC Advances. 2015; 5: 65: 52642-52657. https://doi.org/10.1039/C5RA08078A

[13] Naresh Kumar T, Vishnu Vardhan K, Hari Krishna M, Nagaraja PV. Effect of graphene oxide on strength properties of cementitious materials: A review. Materials Today: Proceedings. 2021; 46: 6: 2157-2160. https://doi.org/10.1016/j.matpr.2021.02.637

[14] Li W, Li X, Chen SJ, Long G, Liu YM, Duan WH. Effects of nanoalumina and graphene oxide on early-age hydration and mechanical properties of cement paste. Journal of Materials in Civil Engineering. 2017; 29: 9: 1-7. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001926

[15] Li W, Li X, Chen SJ, Liu YM, Duan WH, Shah SP. Effects of graphene oxide on early-age hydration and electrical resistivity of Portland cement paste. Construction Building Materials. 2017; 136: 506-514. https://doi.org/10.1016/j.conbuildmat.2017.01.066

[16] Li X, Korayem AH, Li C, Liu Y, He H, Sanjayan JG, Duan WH. Incorporation of graphene oxide and silica fume into cement paste: A study of dispersion and compressive strength. Construction Building Materials. 2016; 123: 327-335. https://doi.org/10.1016/j.conbuildmat.2016.07.022

[17] Akshana V, Naveen Arasu A, Karthigaiselvi P. Experimental study on concrete by partial replacement of cement by silica fume. Journal of Critical Reviews. 2020; 7: 17: 3801-3805.

[18] Bajpai P, Choudhary K, Srivastava A, Sangwan KS, Singh M. Environmental impact assessment of flyash and silica fume based geopolymer concrete. Construction Building Materials. 2020; 254: 120-147. https://doi.org/10.1016/j.jclepro.2020.120147

[19] Süleyman Gökçe H, Hatungimana D, Ramyar K. Effect of fly ash and silica fume on hardened properties of foam concrete. Construction Building Materials. 2019; 194: 1-11. https://doi.org/10.1016/j.conbuildmat.2018.11.036

[20] Golewski GL, Gil DM. Studies of Fracture Toughness in Concretes Containing Fly Ash and Silica Fume in the First 28 Days of Curing. Materials. 2021; 14: 319: 1-21. https://doi.org/10.3390/ma14020319

[21] Wang Y, Cao Y, Ma Y, Xiao S, Hu J, Wang H. Fresh and hardened properties of alkali-activated fly ash/slag binders: effect of fly ash source, surface area, and additives. Journal Sustainable Cement. 2022; 239-262. https://doi.org/10.1080/21650373.2021.1932637

[22] Das SK, Mustakim SM, Adesina A, Mishra J, Alomayri TS, Assaedi HS, Kaze CR. Fresh strength and microstructure properties of geopolymer concrete incorporating lime and silica fume as replacement of fly ash. Journal of Building Engineering, 2020; 32: 101780. https://doi.org/10.1016/j.jobe.2020.101780