Research Article

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Ultrafine GGBS and Ultrafine Fly Ash as Cement Replacement to Mitigate the Environmental Impact of Concrete

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ABSTRACT

Concrete is used as a construction material using all over the world, contributing most important role to infrastructure development. However, it has long been recognized for its environmental footprints. This research paper will provide a study where ultrafine fly ash and ultrafine GGBS are used to maximize cement replacement in concrete without compromising its mechanical properties and achieving a more sustainable concrete, comprehensive review of the environmental impacts of concrete included production, empirical data, statistical analyses, and supplementary materials to mitigate its adverse effects. Drawing upon theoretical frameworks, empirical data, and statistical analysis, this paper evaluates the efficacy of various strategies in reducing the carbon footprint, energy consumption, and resource depletion associated with concrete production. Through overview of CCU, recycled and reuse of materials and an examination of alternative material and best practices, this paper offers insights into the current state of sustainable concrete production and identifies opportunities for future research and development.

Keywords: Sustainable concrete; Ultrafine GGBS; Ultrafine fly ash; Mineral admixture; Carbon capture and utilization.

1. INTRODUCTION

Concrete is most widely used mad made construction material in the world. It is obtained by rationally chosen mixture of Cement, fine aggregate, coarse aggregate water and sometimes admixtures. Besides being the most widely used construction material, concrete production has some environmental consequences (Magandeep *et al.* 2015). The major component of concrete which is responsible for this negative impacting nature is cement. According to data from the International Energy Agency (IEA), the cement industry alone accounts for approximately 7% of emission of carbon dioxide (CO_2) globally, making it one of the largest contributors to anthropogenic greenhouse gas emissions. Furthermore, concrete production consumes large amounts of energy and natural resources, including water, aggregates, and raw materials such as limestone, clay etc. (Ramalekshmi *et al.* 2014).

1.1 Carbon Emission

The major component of concrete which is responsible for this negative impacting nature is cement. Cement is also widely used for various construction purposes but during manufacturing of cement lot of dangerous gases are released such as carbon monoxide and carbon dioxide in the same way the hazardous waste such as highly alkaline materials and volatile organic compounds. Due to this hazardous waste the different types of diseases are caused, and it also causes problem in eco-system which leads to environmental imbalance. In this way by using supplementary cementitious material, we can reduce the environmental imbalance and maintain the eco-system in the safe way. The production of one ton of cement typically emits around 0.8 to 1.0 ton of carbon dioxide

1.2 Energy Consumption

- Energy Intensive Process: In Concrete the cement manufacturing is one of the most energy-intensive industries globally. The production process involves raw material preparation, clinker production, and cement grinding, each requiring significant amounts of energy.
- Global Energy Use: The International Energy Agency (IEA) estimates that the cement industry accounts for approximately 7% of global industrial energy use. The main energy-intensive processes include the grinding of raw materials, the calcination of limestone to produce clinker, and the grinding of clinker into cement.

1.3 Resource Depletion

Concrete production consumes natural resources, including sand, gravel, and water.

- Aggregate Extraction: Concrete production relies on the extraction of natural resources, including aggregates such as sand, gravel, and crushed stone. The extraction of aggregates can lead to habitat destruction, erosion, loss of biodiversity, ecosystem degradation, and depletion of natural reserves.
- Water Consumption: Concrete production also requires significant amounts of water for mixing and curing. The extraction of water for concrete production can exacerbate water scarcity issues in regions with limited water resources.
- Sand Extraction: Sand is also a critical component of concrete and is the most consumed raw material after freshwater in concrete. However, the extraction of sand can have significant environmental consequences, including habitat destruction, erosion of riverbanks, and disruption of aquatic ecosystems. According to United Nations Environment Programme (UNEP) the sand extraction has tripled globally over the last two decades, leading to significant environmental impacts on river ecosystems and coastal areas.

2. THERORETICAL FRAMEWORKS

2.1 Life Cycle Assessment

LCA is a methodology to evaluate the environmental impacts of a product or process throughout their entire lifecycle, from being raw material to end-of-life disposal. LCA studies provide insights into the environmental footprint of concrete production, considering factors such as carbon emissions, energy consumption, resource depletion, and ecosystem impacts.

2.2 Cradle-to-cradle Design

Cradle-to-cradle design principles focused on the creation of products and systems that mimic natural ecosystems, where waste is used as a resource and continuously cycled back into the production process. Cradle-to-cradle design approach encourage the development of closed-loop systems for concrete production, promoting material reuse, recycling, and resource recovery.

2.3 Circular Economy Principles

Circular economy principles aim to minimize waste and maximize resource efficiency by promoting strategies such as material reuse, remanufacturing, and recycling. In the context of concrete production, circular economy principles support the use of recycled materials, of recycled aggregates, supplementary cementitious materials, and alternative binders and innovative technologies to reduce environmental impact and conserve resources.

3. SUSTAINABLE PRACTICES IN CONCRETE PRODUCTION

3.1 Use of Supplementary Cementitious Materials

The Supplementary Cementitious material (SCMs) such as fly ash, GGBS, and silica fume, can be used as a replacement of cement in the construction work to minimize the drawbacks of normal concrete such as the emission of carbon dioxide so as to be eco- friendly. These materials are industrial by-products or waste materials. By incorporating SCMs into concrete mixtures, we can reduce the amount of clinker required, thus it will reduce the CO_2 emission. According to a study published in the Journal of Cleaner Production, replacing 25% of cement with fly ash can reduce CO_2 emissions by up to 40-50%.

- Fly Ash: Fly ash is a byproduct of coal combustion in power plants and can be used as a supplementary cementitious material in concrete production. Incorporating fly ash into concrete mixtures reduces the demand for Portland cement, thereby it reduces the carbon dioxide emission.
- Slag: Ground granulated blast furnace slag (GGBFS) is a byproduct of iron and steel manufacturing and can be used as a partial replacement for cement in concrete. Slag-based concrete offers environmental benefits, including reduced CO_2 emissions and improved durability. (Karri *et al.* 2015)
- Silica Fume: Silica fume is a by-product of silicon metal production and can be used as a supplementary cementitious material in concrete. Silica fume improves concrete strength, durability, and resistance to chemical attacks.

3.2 Alternative Binders

Alternative binders can be a good option to reducing the environmental impact of concrete production. These binders, such as calcium sulfoaluminate (CSA) cement, magnesium-based cement, and alkali-activated materials, have lower carbon footprints compared to traditional Portland cement. For instance, CSA cement production emits approximately 30-40% less CO_2 compared to Portland cement, according to research conducted by the Massachusetts Institute of Technology (MIT). Alternative binders often utilize industrial by-products or natural materials as feedstocks, reducing the need for virgin raw materials and minimizing waste generation.

- Calcium Sulfoaluminate (CSA) Cement: CSA cement is an alternative binder that produces lower carbon emissions compared to traditional Portland cement. CSA cement production emits approximately 30-40% less CO_2 per ton compared to Portland cement, making it a more sustainable option for concrete production.

- Magnesium-Based Cement: Magnesium-based cement is an emerging alternative binder that utilizes magnesium oxide (MgO) as the primary ingredient. Magnesium-based cement production has the potential to reduce carbon emissions and energy consumption compared to Portland cement, while also offering enhanced durability and performance.
- Alkali-Activated Materials: Alkali-activated materials, such as geopolymers and alkali-activated slag, are alternative binders that utilize industrial byproducts and waste materials as feedstocks. These materials offer environmental benefits, including reduced carbon emissions, energy consumption, and depends on raw materials.

3.3 Carbon Capture and Utilization

Emerging technologies, such as carbon capture and utilization (CCU) have potential to reduce CO_2 emissions from cement plants up to 70-80% when coupled with enhanced oil recovery or mineralization processes (Global CCS Institute), and CCU can convert them into valuable products, such as aggregates, chemicals, or fuels. CCU technologies have the potential to significantly reduce the carbon footprint of concrete production while creating new revenue streams.

3.4 Recycling and Reuse of Concrete Waste

Recycling concrete waste from demolition and construction activities can reduce the demand for virgin aggregates and the environmental impact of concrete production. Concrete waste can be crushed and processed into recycled aggregates for use in new concrete mixtures, it will reduce the demand of virgin aggregates and minimizing waste disposal. The European Commission estimates that recycling concrete waste can save up to 1.5 tons of CO_2 emissions per ton of recycled concrete produced, compared to conventional concrete production. Additionally, recycling concrete waste helps alleviate pressure on landfills, conserves natural resources and supports circular economy principles.

4. INNOVATIONS IN SUSTAINABLE CONCRETE TECHNOLOGIES

4.1 Alkali-activated Binders

Alkali-activated binders, such as geopolymers and alkali-activated slag can be used as alternatives to Portland cement, with lower carbon emissions and improved durability. These binders utilize industrial by-products, such as fly ash and slag, and require lower curing temperatures, resulting in energy savings and reduced environmental impact.

4.2 Geopolymer Concrete

Geopolymer concrete, synthesized from aluminosilicate precursors and alkali activators, exhibits comparable or superior mechanical properties to traditional concrete, with lower greenhouse gas emissions and resource consumption. Geopolymer concrete can utilize a wide range of industrial by-products, including fly ash, slag, and mine tailings, as feedstocks. Geopolymer concrete offers environmental benefits, including reduced CO_2 emissions, energy consumption, and reliance on Portland cement.

4.3 Nano-engineered Concrete

Nano-engineered concrete incorporates nanomaterials, such as nanoparticles, nanofibers, and nanotubes, to enhance mechanical properties, durability, and sustainability. Nanomaterials can improve concrete strength, reduce water and cement content, and mitigate cracking and deterioration, leading to longer service life and reduced environmental impact.

4.4 3D printing Technology

3D printing technology enables the rapid fabrication of complex concrete structures with minimal material waste and energy consumption. By precisely controlling material deposition and optimizing structural design, 3D printing can achieve material-efficient and sustainable construction solutions for a variety of applications, including housing, infrastructure, and urban furniture.

4.5 Self-healing Concrete

Self-healing concrete incorporates microorganisms, encapsulated healing agents, or vascular networks to autonomously repair cracks and damage, prolonging service life and reducing maintenance requirements. Self-healing mechanisms can mitigate concrete deterioration caused by environmental factors, such as freeze-thaw cycles, chemical attack, and mechanical loading, leading to more sustainable infrastructure systems.

5 EMPIRICAL DATA AND SATISTICAL ANALYSIS

5.1 Environmental Impact Assessment

Life cycle assessment (LCA) studies have compared the environmental performance of traditional and sustainable concrete mixtures, quantifying reductions in carbon emissions, energy consumption and resource depletion. A meta-analysis published in the Journal of Cleaner Production founds that sustainable concrete mixtures generally exhibit lower global warming potential, acidification potential, and eutrophication potential compared to conventional concrete.

5.2 Cost-benefit Analysis

Cost-benefit analysis (CBA) studies have evaluated the economic feasibility of sustainable concrete practices and technologies, considering initial investment costs, operational expenses, and long-term savings. Research conducted by the World Business Council for Sustainable Development (WBCSD) suggests that the implementation of sustainable concrete solutions can result in net cost savings over the life cycle of a project, accounting for factors such as material costs, construction time, and maintenance expenses.

6. EXPERIMENT

The production of 1 tone of Portland cement results in an equal amount of CO_2 emission into the atmosphere which is a major cause for greenhouse effect. So the use of mineral admixtures such as Fly ash, Ground Granulated Blast Furnace Slag, Micro Silica in concrete as a partial replacement of cement reduces the burden of greenhouse effect, save energy and conserves natural resources. The most important objective of this study is to assess the chances of usage of GGBS (Ground Granulated Blast Furnace Slag) in Concrete. The enhancement in a technology requires studying effects caused by the mineral admixture on the strength of the cementitious materials. Ground Granulated Blast furnace Slag is obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. Ground-granulated blast furnace slag is highly cementations and high in calcium silicate hydrates (CSH) which is a strength enhancing compound which improves the strength, durability and appearance of the concrete. Ultrafine fly ash is a processed ash generated from a Class F fly ash source. The parent ash is passed through a classifier where the coarse particles are removed and the fines are collected and stored separately.

6.1 Materials

The materials used in this investigation are Portland pozzolana cement (PPC), commercially available coarse aggregate of crushed rock with size of 20 mm and 12 mm, fine aggregate of clean river sand, potable water.

Table 1. Physical properties of pozzolana Portland cement

Physical Properties	Test Values	Requirements as per IS
Fineness	4.33%	IS:4031–Part-1-1996
Standard Consistency	29.5%	IS:2269-1987
Initial Setting Time	169 Minutes	Minimum of 30 minutes
Final Setting Time	220 Minutes	Maximum of 600 minutes

Table 2. Physical properties of fine aggregate

Characteristics	Obtained value
Type	Natural sand
Fineness modulus	2.76
Specific gravity	2.54
Grading zone	Zone 3
Water absorption	1.6%

Table 3. Physical properties of coarse aggregate

Properties	Coarse Aggregate	
	12.5 mm	20 mm
Fineness Modulus	6.61%	7.0%
Specific Gravity	2.74	2.74
Water Absorption	0.40%	2.05%

Table 4. Properties of ground granulated blast furnace slag

Test Conducted	Result	Requirement as per IS:16715-2018
Sample Name	GGBS	Maximum 5.5
Specific Gravity	2.86	Not Specified
Slag Activity Index as percent of control sample		
7 days	90.0	Not less than 85 %
28 days	107	Not less than 100 %
Glass Content (%)	98.9	Maximum 5.5
Manganese Oxide (MnO) (%)	0.24	Maximum 17.0
Magnesium Oxide (MgO) (%)	8.28	Maximum 2.0
Sulphide Sulphur (S) (%)	0.50	Maximum 3.0
Sulphate (as SO_3)	0.10	Maximum 3.0
Insoluble residue (Max.) (%)	0.16	Maximum 3.0
Chloride Content	0.004	Maximum 0.1
Loss on Ignition	0.15	Maximum 3.0
$(CaO+MgO+1/3.Al_2O_3)/(SiO_2 + 2/3\ Al_2O_3)$	1.10	Maximum 1.0
$(CaO+MgO+Al_2O_3)/(SiO_2)$	1.83	Minimum 85.0

Table 5. Properties of ultrafine flyash

Test Conducted	Result	Requirements as per IS:3812-2013	
Sample Name	Ultrafine Fly ash	Part - I	Part - II
Specific Gravity	2.75	-	-
Fineness – specific Surface in (m3/kg) by Blaine's Air Permeability method	428	Minimum 320	Minimum 200
Lime reactivity – Average Compressive Strength in (N/mm^2)	12.0	Minimum 4.5	-
Compressive Strength at		-	
28 days N/mm^2		-	
Test Sample	34.0	Not less than 80% of the strength of corresponding plain cement mortar cube	-
Plain Cement mortar cube	36.0		
Comparative Strength in percent	94.0		
Soundness by Autoclave test Explaining of specimens percent	0.027	Maximum 0.8	Maximum 0.8
Residue on 45 micron sieve, Percent	Nil	Maximum 34	Maximum 50

Table 6. Properties of super plasticizer

Appearance	Light yellow colored liquid
pH	Minimum 6.0 *
Volumetric mass @ 200 C	1.09 kg/liter
Chloride content	Nil to IS:456-2000*
Alkali content	Typically less than 1.5 g Na_2O equivalent / liter of admixture

6.2 Casting, Curing and Designation of Samples

After casting, the specimens were left for 24 hours in the laboratory environment (22 ± 3 °C) to minimize loss of mix water. After 24 hours, the specimens were de-moulded and placed in a curing tank till the time of test.

For the efficacy evaluation of various replacement compounds, the specimens were evaluated for six parameters which included compression, density, workability, split tensile, absorption and sorptivity. A total of six categories of concrete specimens were studied including the control specimens, specimens from blending compound of UFFA and GGBS. 300 cube specimens of dimension (150 x 150 x 150) mm were tested. Compression test and Split Tensile Test was conducted at the age of 7 days and 28 days after casting.

6.3 Results and Discussion

The results are on different percentages of Ultrafine GGBS as i.e. 15%, 20%, 25% and 30% with 20% of Ultrafine Fly ash as cement replacement named as A, B, C and D respectively.

6.3.1 Workability

Super Plasticizer with UFFA and GGBS was added at the time of mixing of concrete showed the maximum slump of 175 mm. The slump cone test was performed on different mixes of concrete to determine workability. The test was performed as per IS:1199-(1959).

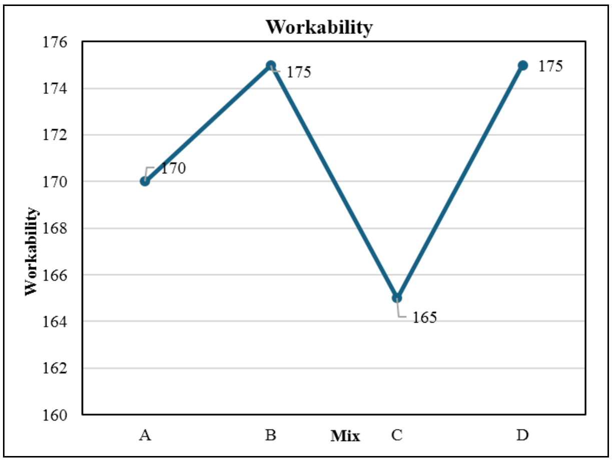

Fig. 1: Workability

6.3.2 Density

The specimens were tested for density, and it was observed that there is no marginal difference in different mixes of concrete. Fig. 2 depicts the test results.

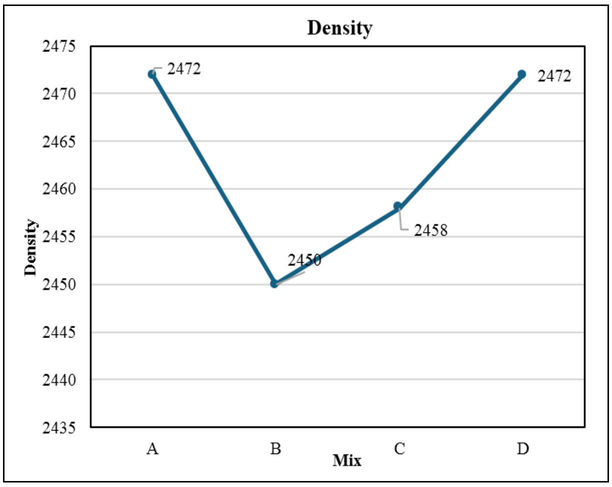

Fig. 2: Density

6.3.3 Water Absorption

Water absorption was conducted on cube specimens of dimension (150 mm x 150 mm x 150 mm). These specimens were oven dried followed by cooling and were then immersed in water for a period of 48 hours and 24 hours were recorded. A graph is plotted against this value which is shown in the Fig. 3.

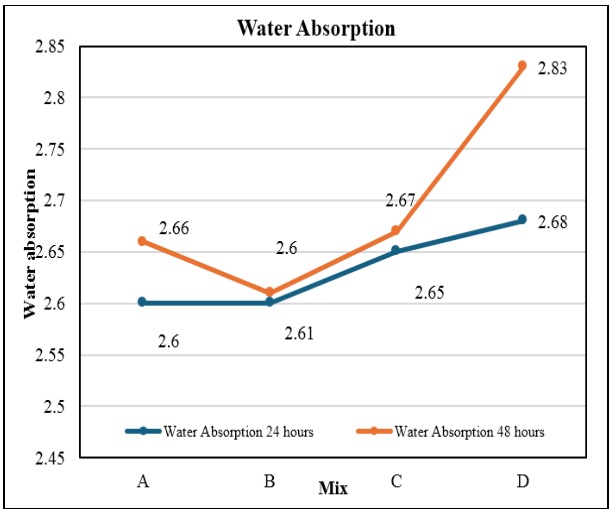

Fig. 3: Water absorption

6.3.4 Compressive Strength

The compressive strength test was performed on cubes (150 mm x 150 mm x 150 mm) of different concrete mixes after 7th day and 28th day of curing to determine their respective compressive strength. The 7 days and 28 days compressive strength result of the specimens is given by Fig. 4 and Fig. 5 respectively.

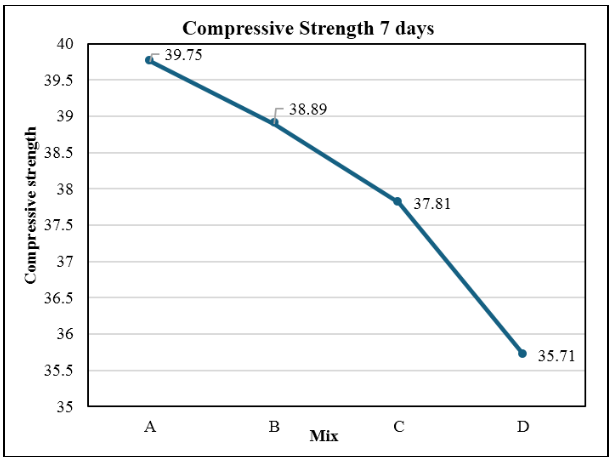

Fig. 4: Compressive strength (7 days)

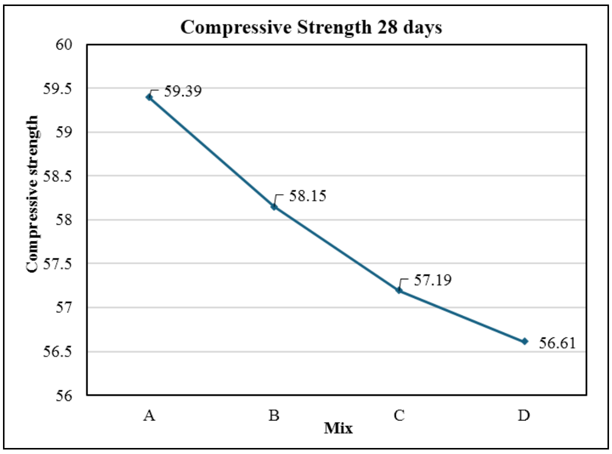

Fig. 5: Compressive strength (7 days)

6.3.5. Split Tensile Strength

The split tensile test was performed as per IS 516 and IS 5816 on the cubes (150 mm x 150 mm x 150 mm) of different concrete mixes to determine the respective split tensile strength of the specimens. Fig. 6 depicts the 28 days split tensile strength of all concrete mixes.

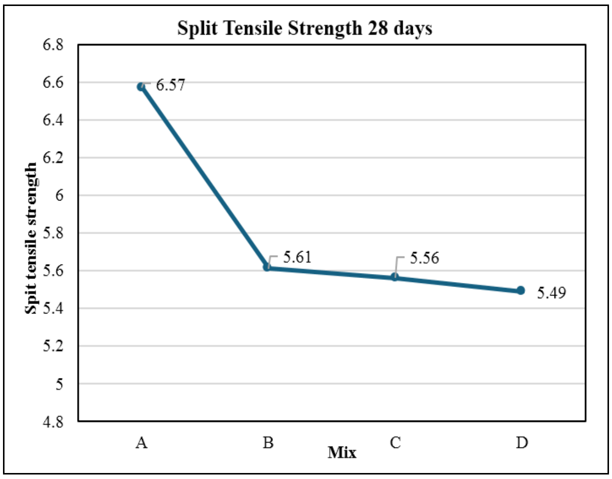

Fig.6: Split tensile strength (28 days)

6.3.6 Sorptivity

Sorptivity test was conducted on cube specimens of dimension (150 x 150 x150) mm. The sorptivity values were recorded for a period of 2 hours at an interval of 30 minutes shown in Fig. 7.

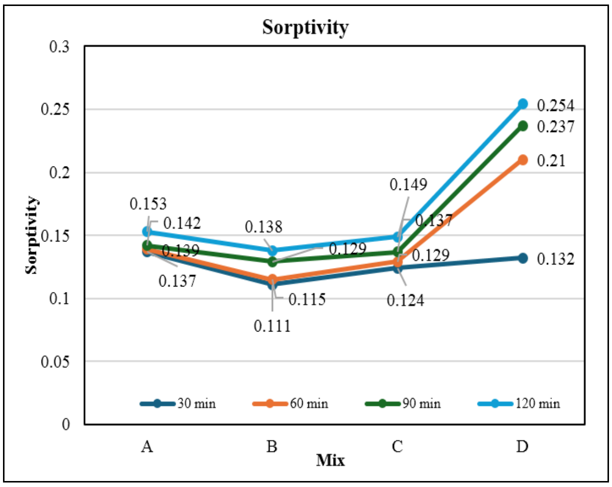

Fig. 7: Sorptivity

- The average sorptivity for the period of 2 hours was also calculated shown in Fig 8.

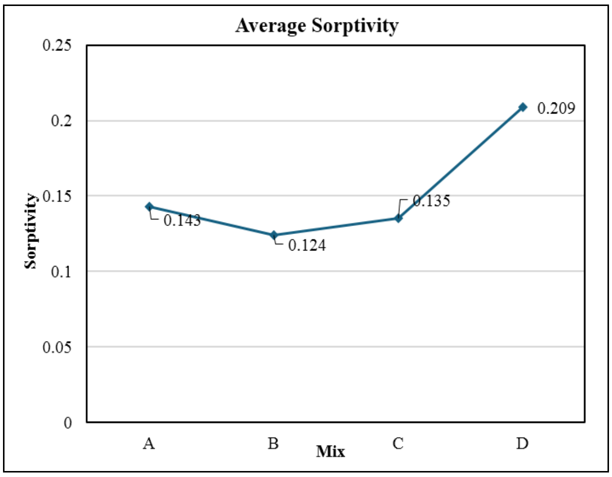

Fig. 8: Average sorptivity

6.3.7 Relationship between compressive strength and split tensile strength

The relationship between compressive strength and split tensile strength was derived using MS Excel linear regression computation. The governing equation is given by:

$$Y = 2.137x - 45.425 \qquad (1)$$

$$R^2 = 0.8976 \qquad (2)$$

Where, y= Average compressive strength (28 days), x= Split tensile strength (28 days), R^2= Coefficient of determination

The observed and predicted values of compressive strength is given in fig 9.

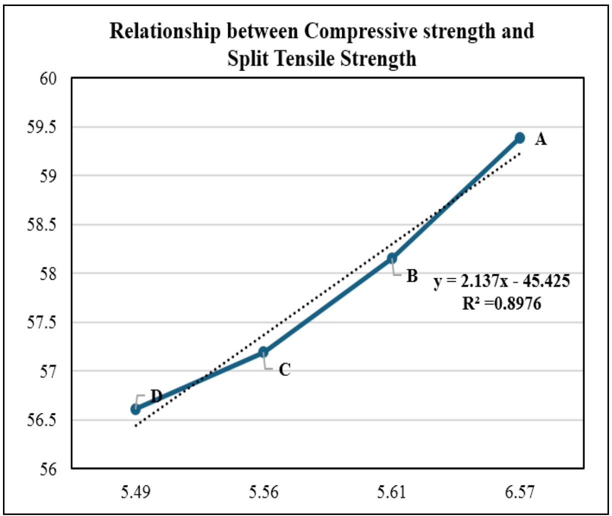

Fig. 9. Relationship between Compressive and Split Tensile Strength

6.3.8 Percentage error

The percentage error in observed and predicted values is given in Table 7 and Fig. 10.

Table 7. Percentage error

Compressive Strength (N/mm^2) at 28 days		Error (%)
Observed	Predicted	
59.39	59.46	-0.12
58.15	57.41	1.29
57.19	57.31	-0.21
56.61	57.16	-0.96

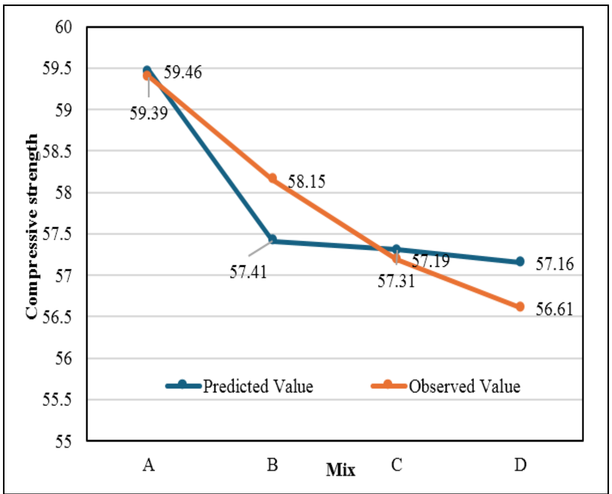

Fig. 10. Predicted and Observed Compressive Strength

7. CONCLUSION

From the study carries out the following conclusions were drawn:

1. The workability decreases with the increase in the percentage of blending of ultrafine flyash and GGBS material, but maintained by using admixture.
2. The density of blending of ultrafine flyash and GGBS decrease with the increase in the percentage of blinding of ultrafine flyash and GGBS.
3. The Water Absorption increase slightly with the addition of blending of ultrafine flyash and GGBS.
4. The Compressive strength of blending of ultrafine flyash and GGBS concrete increase with the increase of blending of ultrafine flyash and GGBS up to total replacement of 30% in which 15% of ultrafine flyash and 15% GGBS and decrease hear after.
5. The Split tensile strength of blending of ultrafine flyash and GGBS concrete increase with the increase of blending of ultrafine flyash and GGBS up to total replacement of 35% in which 20% of ultrafine flyash and 15% GGBS and decrease hear after.

In this study it can be concluded that use of blending ultrafine flyash and Ground Granulated Blast Furnace Slag waste as a replacement of cement in combination is feasible and it shows positive result for compressive and split tensile strength test of concrete. Making Concrete with the Combination of ultrafine flyash and GGBS and cement with different percentage gives good results compared to control concrete. So the best way to use these materials is in combination. Due to environmental issues in the production of cement, industrial by products like ultrafine fine flyash and GGBS are used as supplementary materials in concrete and its saves cost of production of concrete, and make it eco-friendly.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

IS:1199-(1959), Method of sampling and analysis of concrete Bureau of Indian standards, New Delhi., Method of sampling and analysis of concrete Bureau of Indian standards, New Delhi., 1959.

IS:16715-2018, Ultrafine Ground Granulated Blast Furnace Slag, Bureau of Indian standard Institution, New Delhi,

IS:2269-1987, Ordinary Portland Cement, 53 Grade — Specification, Bureau of Indian standard Institution, New Delhi, Ordinary Portland Cement, 53 Grade — Specification, Bureau of Indian standard Institution, New Delhi, 1989.

IS:3812-2013, Pulverized fuel ash — specification, Part 1 for use as pozzolana in cement, Cement Mortar And Concrete, Bureau of Indian standard Institution, New Delhi, Pulverized fuel ash — specification, Part 1 for use as pozzolana in cement, Cement Mortar And Concrete, Bureau of Indian standard Institution, New Delhi, 2013.

IS:4031–Part-1-1996, Method of Physical Tests for Hydraulic Cement Part 1 Determination of Fineness by Dry Sieving, Bureau of Indian standard Institution, New Delhi, Method of Physical Tests for Hydraulic Cement Part 1 Determination of Fineness by Dry Sieving, Bureau of Indian standard Institution, New Delhi, 1996.

IS:456-2000, Specifications for plain and reinforced concrete, Bureau of Indian standards, New Delhi., Specifications for plain and reinforced concrete, Bureau of Indian standards, New Delhi., 2000.

Karri, S. K., Rao, G. V. R., Raju, P. M., Strength and Durability Studies on GGBS Concrete,

Magandeep, Pareek, R. K., Singh, V., Utilization of Ground Granulated Blast Furnace Slag to Improve Properties of Concrete, *Int. J. Emerg. Technol.* 6(2), 72–79 (2015).

Ramalekshmi, M., Sheeja, R., Gopinatp, R., Experimental Behavior of Reinforced Concrete with Partial Replacement of Cement with Ground Granulated Blast furnace Slag, Int J Eng Res Technol. 3(3), (2014). https://doi.org/10.17577/IJERTV3IS030735