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Development and performance characterization of eco-friendly ternary blended concrete using industrial and agricultural waste materials

ABSTRACT

This current research attempts to explore the effect of mineral admixtures like rice husk ash (RHA), metakaolin, and GGBFS on the physical, mechanical and durability behaviors of M40 grade concrete. Different mixes of concrete were prepared using partial replacements of GGBS, metakaolin, and RHA instead of cement. Tests of slump flow, L-box test, V-funnel, J-ring, and U-box were conducted to evaluate new properties. After different curing periods, mechanical properties like bending strength, splitting tensile strength, and compressive strength were evaluated. It was revealed that addition of metakaolin improves early strength and density of microstructure while the usage of GGBS improves workability and strength. A combination of 10% metakaolin and 20% GGBS was found to be the most efficient one. The inclusion of RHA increased performance up to 5-10% but reduced strength and workability more than 10%. Reduced water absorption rate, resistance to chloride attack and acid &sulfate environment was observed in durability analysis.

***Keywords**: GGBS, metakaolin, rice husk ash*

1. INTRODUCTION

Due to growing sustainability concerns in the field of construction materials, there is considerable interest in exploring the use of supplementary cementitious materials (SCMs) like GGBS, MK, and RHA in order to partially replace OPC. The production process of cement produces about 7-8% of the world's total carbon dioxide emissions. SCM partial substitution (20-50%) reduces the environmental footprint of the materials. These materials have been extensively studied in different types of concrete like normal, HPC and SCC.

The use of MK and RHA greatly influences the fresh properties due to the very fine particle size and large specific surface area of the materials. The enrichment in water demand of 5-15% due to use of MK (specific surface area 12 m²/g) and RHA (0.16-25 m²/g) leads to decreased slump values. [1].

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A decrease in slump values of 20-40% have been noted when the amount of RHA increased from 10% to 30%. For SCC, the use of 10-15% of MK and 10-20% RHA gives slump flow values between 650 mm and 750 mm as per EFNARC criteria. [2]. Higher percentage of GGBS replacement up to 30-45% improves workability due to the smooth particle shape of the GGBS. [3] With increased amounts of RHA in alkali-activated concrete, slump value decreases from around 180 mm to 100 mm and unit weight also decreased by 5-8% due to lesser density and lower workability. [4] The workability of geopolymer mixes becomes optimum at 0.45-0.50 water/binder ratio and alkali/precursor ratio of 0.4 [5].

Performance of blended systems mechanically is greatly enhanced when there is an optimum ratio of SCMs used. A ternary blend consisting of 10% MK+10% GGBS+15% RHA will improve the compressive strength by 15-30% in 28 days, relative to control OPC. [2, 6] Compressive strengths of 45-60 MPa will be achieved, compared to 35-45 MPa of conventional concrete. In case of

SCC, blending 10% MK and 10-20% RHA will yield compressive strengths of 50-65 MPa after 28 days with increased strengths of 70 MPa after 90 days [4, 5, 7]. Other strengths include splitting tensile of 10-20% improved values and flexural strength of 8-15% [8]. In alkali-activated GGBS concrete, addition of 5-10% RHA yields compressive strengths of 40-65 MPa, although addition of >20% of RHA causes reduction in compressive strength of 10-25% due to decreased binder reactivity [9] .

The use of MK and RHA also greatly improves durability through decreased permeability and pore refinement. The absorption rate drops by 15–35%, while sorptivity decreases by 20–40% when using 10–15% MK and 10–15% RHA [10]. Rapid chloride permeability (RCPT) drops from 3000–4000 coulombs (moderately permeable) in OPC concretes to 1000–2000 coulombs (less permeable) in blends [7,11]. There is a drop in chloride diffusion by up to 50%, making these concretes more resistant to corrosion. Permeability reduction in the range of 30–60% and increased sulphate resistance can be achieved in ternary mixes. With the use of 5–10% of RHA in GGBS concretes, there is 10–25% reduction of permeable voids and 15–20% improvement of carbonation resistance [12]. Resistance to acids is investigated and shows up to 20–40% lower mass loss in blends compared to OPC. Correctly treated RHA, with a high percentage of silica content (~85–90% SiO_2), can be used to replace up to 30% of OPC without compromising durability [13].

Microscopic studies show that the role of SCMs is that of promoting hydration reactions and creating denser microstructures. Pozzolanic reactions between silica-containing materials (i.e., RHA ~89% SiO_2, MK ~52% SiO_2) and calcium hydroxide lead to more C-S-H and C-A-S-H gels, thus increasing the quantity of gels by ~20-35% [14]. SEM studies indicate the reduction in the size of pores from 100-500 nm in OPC concrete to 10-100 nm in blended concretes. X-ray diffraction shows that portlandite peaks decrease while amorphous contents increase due to enhanced pozzolanic activity [15,16]. For alkali-activated concretes, the formation of N-A-S-H and C-A-S-H gels leads to a dense microstructure. The optimal percentage of RHA for achieving pore refining and minimal permeability in blends is ~10%. Heat treatment (~60°C) causes a further reduction in the number of pores by ~15-25% [17].

According to the research findings, the use of 20–50% of OPC and replacement with SCM is known to minimize CO_2 emission without compromising on the performance of the concrete. The use of MK and RHA lowers the workability of concrete by 20–40% while the use of 30–45% of GGBS increases the workability because of its smooth particle nature. The compressive strength is expected to be enriched by 15–30%. Moreover, there will be an increase in durability due to the improvement of up to 30–60% reduction in permeability and up to 50% reduction in chloride diffusion.

Although there have been developments in the use of these blended materials in concrete, little work has been done that attempts to optimize the mix ratios of OPC 43 cement along with GGBS, MK, and RHA in a quaternary blend. Additionally, investigations for more than 180–365 days and practical implementations are not well studied. This investigation, therefore, is designed to evaluate the effectiveness of a mix of GGBS at (30-45%), MK at (5-15%), and RHA at (5-20%) as OPC 43 grade cement. The focus is on evaluating fresh properties, compressive strength up to 90 days, durability indices, and microstructural characteristics to determine optimal mix proportions for sustainable and high-performance concrete.

2. MATERIALS

2.1. Cement

OPC 43 grade cement is a grey, fine powdered material with a relative density of 3.14. The material has a surface area of 2249 cm^2/g with particles measuring below 90 microns, thereby allowing proper hydration and development of strength. [18] Volume expansion of 3 mm confirms its soundness property. In terms of its chemical composition, the cement is rich in calcium oxide (61.31%) while also possessing silica (20.11%), alumina (4.53%), and iron oxide (2.54%) elements. Elements such as magnesia (1.08%) and loss on ignition (2.49%) confirm that the cement is stable, making it ideal for use in construction applications. Figure 1 gives an illustration of the XRD of OPC 43 grade.

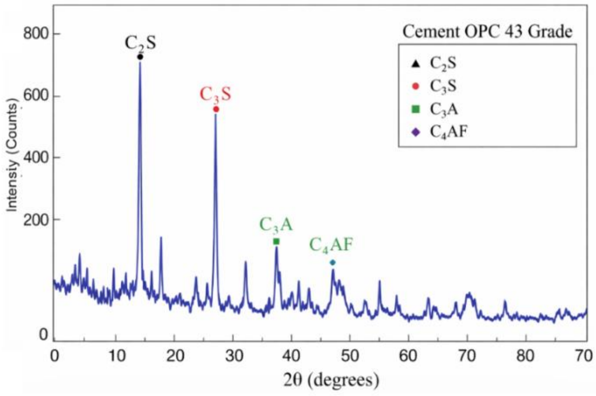

Figure 1. XRD of cement

2.2. GGBS

GGBS is a light grey powder that has a relative density of 2.93 and bulk density of 1090 kg/m³. Its specific surface area is 0.37 m²/g, and the particle size is more than 75 µm, signifying moderate fineness. [19] In terms of chemical composition, it contains a high amount of calcium oxide (38.46%) and silica (29.32%), along with considerable amounts of alumina (16.91%) and magnesia (7.59%). Sodium oxide, iron oxide, sulphur trioxide, potassium oxide, and manganese oxide are some of the trace elements in GGBS. The lower loss on ignition of 2.23% indicates its purity and stability. Figure 2 shows the XRD image of GGBS.

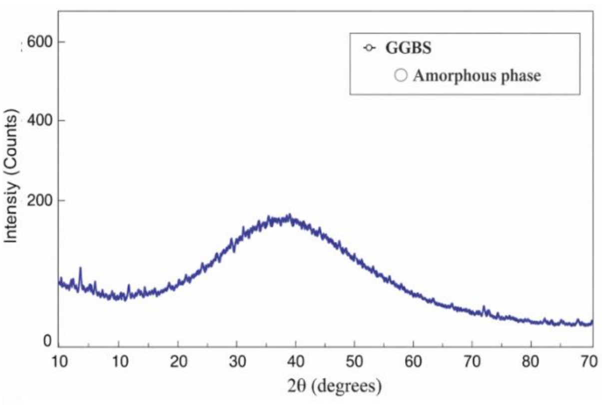

Figure 2. XRD image of GGBS2.3. Metakaolin

Metakaolin employed in this study is an extremely reactive white powder that possesses a relative density of 2.58, and a relatively low bulk density of 490 kg/m³. Metakaolin has a very high specific surface area of 12 m²/g, and a very fine particle size of 5 µm as a result of which it exhibits good pozzolanic reactivity. [20] Metakaolin has very high concentrations of silicon dioxide (51.87%) and aluminum oxide (46.12%). Almost no traces of calcium oxide are present in metakaolin. Iron, sodium, magnesium, and potassium oxides exist in minute traces. The loss on ignition percentage of 1.14% is indicative of very high purity of metakaolin.

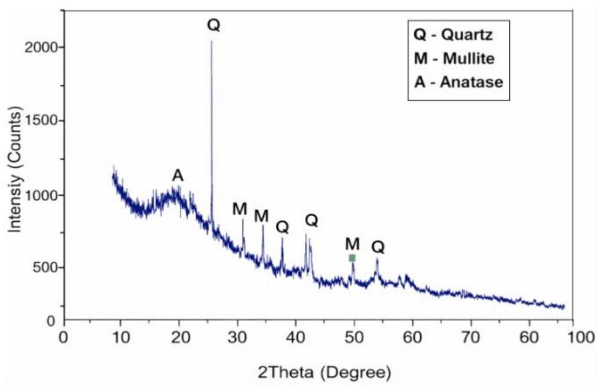

Figure 3. XRD image of metakaolin

2.4. Rice Husk Ash

The RHA is a light grey substance having relative density of 2.15 and specific surface area of 0.16 m²/g. The particle size of this substance is always above 75 µm that denotes higher particle size and thus coarse nature than other pozzolanic materials. [21] Chemical wise RHA is extremely rich in silica content (89.3%) due to which it exhibits excellent pozzolanic activity. There are traces of alumina (2.5%) and iron oxide (2.63%) in RHA along with trace amount of calcium oxide (0.28%). Loss on ignition for RHA is 5.29%, showing that there is carbon present in this material. Figure 4 shows the XRD of RHA.

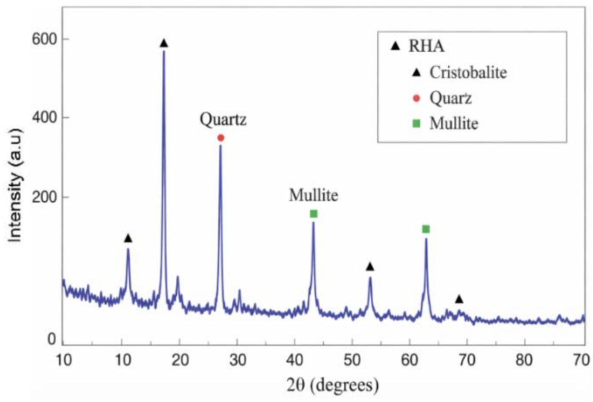

Figure 4. XRD of RHA

2.5. Aggregates

Fine aggregate has a relative density and a water absorption of 2.7 and 1.20%, respectively, suggesting that the aggregate possesses high strength qualities and is moderately porous. The bulk density and fineness modulus of fine aggregates are 2650 kg/m³ and 2.63, respectively, meaning that the material is well-graded and therefore can be used in making concrete. [22] Coarse aggregates have a relative density and water absorption of 2.6 and 0.60%, respectively, and therefore it is highly durable. Other characteristics include bulk density and crushing value of 2500 kg/m³ and 16.20%, respectively, and impact value of 23%, implying that coarse aggregates possess adequate compressive strength and resistance to impact forces. Figures 5 and 6 illustrate particle size distribution.

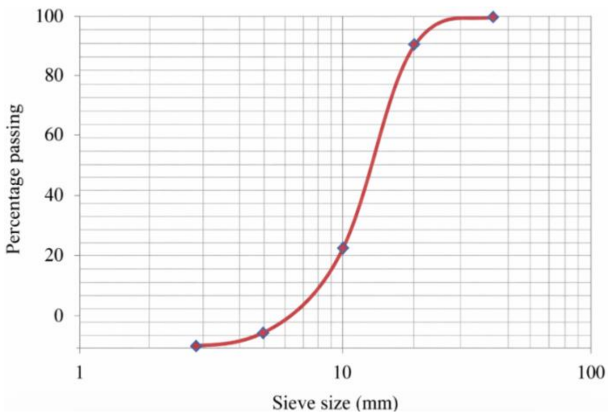

Figure 5. Grain Size Distribution of M-Sand

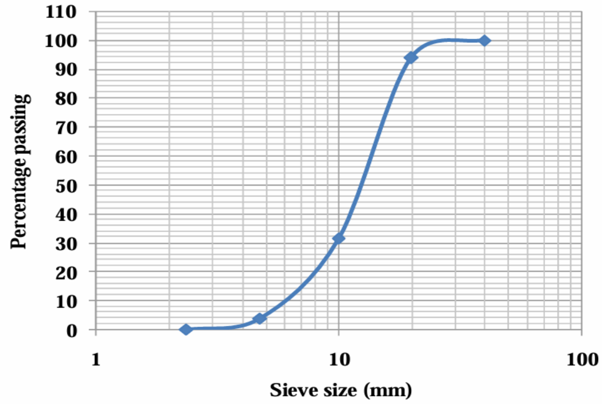

Figure 6. Grain Size Distribution of coarse aggregate

3. METHODOLOGY

Total 12 mixes of concrete were produced for studying the effect of single and combined SCMs. Mix CC was made up of 100% OPC. Other mixes were made by partially substituting cement by GGBS, MK, and RHA in various proportions. GGBS mixes only: 10%, 20%, and 30% by volume substitution of GGBS (GGBS1-GGBS3), binary mixes (GGBS + MK): 20% GGBS and 5-15% MK (GGBDME1-GGBSME3), ternary mixes (GGBS + MK + RHA) and GGBS(10-20%), MK(10%), RHA(5-20%) (GGBDMERHA1-GGBDMERHA5).

M-sand and coarse aggregate proportion was constant throughout the experiments i.e., 100%. However, only cement, GGBS, MK, and RHA proportions were changed to obtain different concrete mixes. Water to binder ratio was set at 0.35 and use of superplasticizer was used for workability improvement. Initially dry material mixing was performed followed by addition of water and superplasticizers. The prepared concrete mix was then cast into molds to make cubes, cylinders, and prism specimens. Specimens were compacted by using vibrating needle to remove air voids from inside.

The fresh concrete workability was tested using the slump test for normal concrete and the slump flow test for SCC based on the relevant standards. Further, other tests like V funnel test and L box tests were conducted for the self-compacting concrete blends to determine their flowability and passability. The compression strength test was done on the cube specimens aged seven days, twenty-eight days, ninety days and one hundred and eighty days through the compression machine. Tensile splitting strength test and flexural strength test were conducted on the cylinder specimens and prism specimens respectively to determine their mechanical properties. Tests for durability of the blended concretes were conducted on the cube specimens aged twenty eight days, ninety days, one hundred and eighty days and three hundred and sixty five days using the water absorption and rapid chloride permeation test.

Table 1. Mix Designation

Sl. No.	Trail ID	Description
1	CC	Conventional Concrete
2	GGBS1	10% GGBS + 90% Cement + 100% M-sand + 100% Coarse Aggregate
3	GGBS2	20% GGBS + 80% Cement + 100% M-sand + 100% Coarse Aggregate
4	GGBS3	30% GGBS + 70% Cement + 100% M-sand + 100% Coarse Aggregate
5	GGBDME1	20% GGBS + 5% Metakaolin + 75% Cement + 100% M-sand + 100% Coarse Aggregate
6	GGBDME2	20% GGBS + 10% Metakaolin + 70% Cement + 100% M-sand + 100% Coarse Aggregate
7	GGBSME3	20% GGBS + 15% Metakaolin + 65% Cement + 100% M-sand + 100% Coarse Aggregate
8	GGBDMERHA1	20% GGBS + 10% Metakaolin + 5% Rice Husk Ash + 65% Cement + 100% M-sand + 100% Coarse Aggregate
9	GGBDMERHA2	10% GGBS + 10% Metakaolin + 5% Rice Husk Ash + 75% Cement + 100% M-sand + 100% Coarse Aggregate
10	GGBDMERHA3	10% GGBS + 10% Metakaolin + 10% Rice Husk Ash + 70% Cement + 100% M-sand + 100% Coarse Aggregate
11	GGBDMERHA4	10% GGBS + 10% Metakaolin + 15% Rice Husk Ash + 65% Cement + 100% M-sand + 100% Coarse Aggregate

12	GGBDMERHA5	10% GGBS + 10% Metakaolin + 20% Rice Husk Ash + 60% Cement + 100% M-sand + 100% Coarse Aggregate

Microstructural properties were analyzed using SEM. The techniques were used to identify hydration products, pore structure, and phase composition, providing insights into the mechanisms responsible for strength and durability improvements. The experimental results were analyzed by comparing blended mixes with the control mix. Experimental works used to evaluate trends in workability, strength, durability, and microstructure. The optimum mix proportions were identified based on overall performance criteria. Table 1 shows the mix designation.

4. RESULTS AND DISCUSSION

4.1. Workability Test

All the freshly obtained physical properties of different mixes were determined by slump flow test, L-box test, V-funnel test, J-ring test, and U-box test. Control mix had slump of 698 mm along with acceptable passing ability (ratio of L-box test is 0.81) and moderate viscosity (8.7 sec. on V-funnel test). On addition of GGBS (GGBS1-GGBS3), slump flow was observed to increase from 710 mm to 735 mm, whereas L-box ratio increased to 0.89. This shows that better flowability and passing ability have been achieved with the use of GGBS.

Adding metakaolin (GGBDME series) made the workability a little substandard, as seen by lower slump values and longer V-funnel times. This is because metakaolin has smaller particles and needs more water. [23] But the mixes still had good filling and passing ability. Adding rice husk ash (GGBDMERHA series) made the workability go down a lot. The slump flow went down to 640 mm, the L-box ratio went down to 0.70, and the V-funnel time went up to 11 seconds. This means that RHA has a higher viscosity and a lower flow because it is porous and absorbs things. The values for the J-ring and U-box also went up, which means that the passing ability went down and the blocking tendency went up. In general, GGBSmade the workability better, but higher amounts of metakaolin and RHA made the fresh properties substandard. [24] Table 2 shows the workability test results.

Table 2. Workability Test Results

Trail ID	Slump Value (mm)	L box Test Ratio	V-Funnel Test (sec)	J-Ring (mm)	U-Box (mm)
CC	698	0.81	8.7	5.59	23
GGBS1	710	0.84	8.2	5.2	21
GGBS2	725	0.87	7.8	4.9	19
GGBS3	735	0.89	7.5	4.6	18
GGBDME1	720	0.86	8	5	20
GGBDME2	705	0.83	8.5	5.4	22
GGBSME3	690	0.8	9.1	5.9	24
GGBDMERHA1	700	0.82	8.8	5.5	23
GGBDMERHA2	685	0.79	9.3	6	25
GGBDMERHA3	670	0.76	9.8	6.4	27
GGBDMERHA4	655	0.73	10.4	6.9	29
GGBDMERHA5	640	0.7	11	7.5	32

4.2. Strength Properties

The compressive, split tensile, and flexural strengths of each type of mix were examined at 7, 28, 90, and 180 days. The control concrete mixture satisfied the M40 grade concrete requirement as its compressive strength was 44.76 MPa after 28 days. Addition of GGBS (GGBS1-GGBS3) made the concrete mixture have comparable early age strength with higher late age strength up to 54.29 MPa due to pozzolanic action and hydration. Incorporation of metakaolin (GGBDME series) greatly enhanced both early age and late age strengths of the concrete mixtures. Mix GGBDME2 possessed improved strength, compressive strength being 47.39 MPa after 28 days and 54.28 MPa after 180 days. This means that its microstructure and porosity have been improved.

The mixes with GGBDMERHA composition, which consists of GGBS, metakaolin, and RHA, showed varying behaviors in different conditions. The mix GGBDMERHA2 gave maximum compressive strength of 56.77 MPa at 180 days and increased tensile strength of 5.47 MPa and flexural strength of 5.26 MPa. It indicates that this was the best combination of mineral admixtures. However, for compositions containing more than 10% RHA content, the strength gradually decreased because of high water demand and difficulty in handling. Overall, from these experiments, it can be concluded that the partial replacement of RHA by GGBS and metakaolin enhances the mechanical properties, while excessive use of RHA reduces strength. [25]. The compressive, split tensile, and flexural strength test results have been illustrated in Figures 7, 8, and 9.

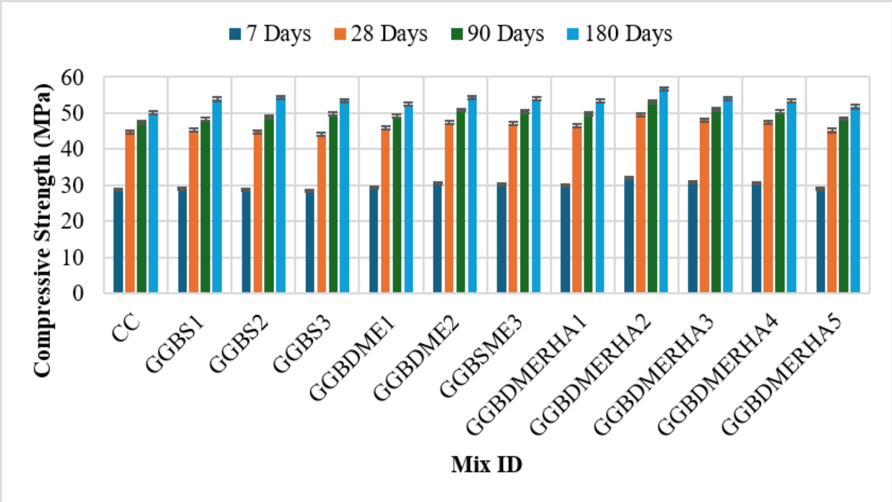

Figure 7. Compressive strength test results

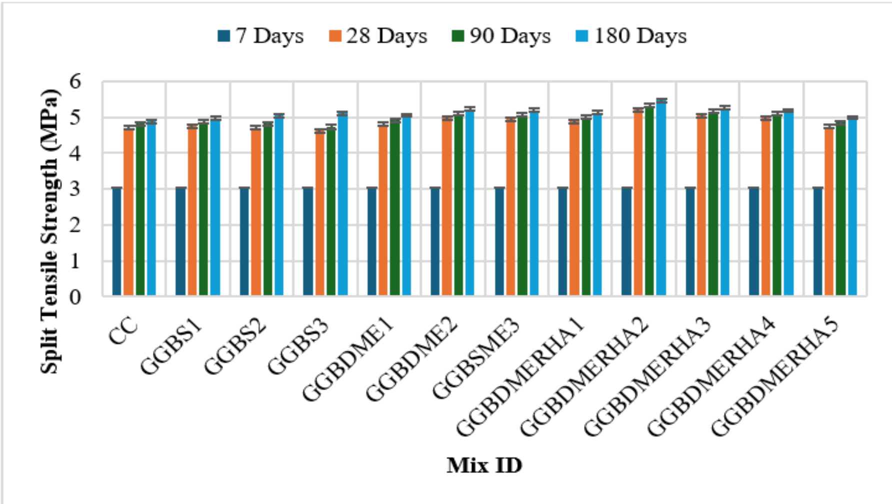

Figure 8. Split tensile strength test results

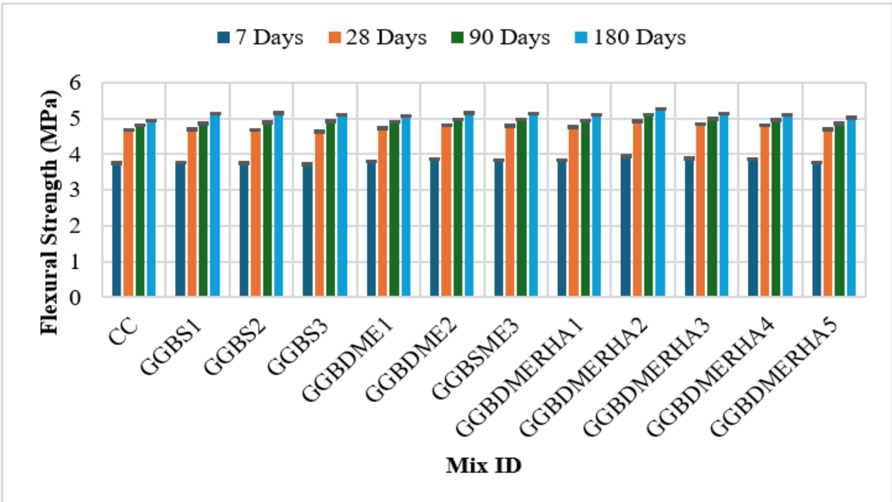

Figure 9. Flexural strength test results

4.3. Durability Properties

We tested the durability of all the concrete mixes by having them absorb water, pass the RCPT, resist acid, and attack sulphate. The control mix (CC) showed that water absorption went down slowly over time, from 3.01% at 28 days to 2.55% at 365 days. This means that the mix became denser over time. GGBS mixes showed similar or slightly better performance, with GGBS1 showing less water absorption because the particles were packed better. Adding metakaolin (GGBDME series) made the product much more durable. Mix GGBDME2 had the lowest water absorption (2.19% at 365 days) and RCPT value (1087 coulombs). This means that it has a dense microstructure and very low permeability. The pozzolanic reaction, which fills internal spaces and refines the pore structure, is responsible for this enhancement.

In the same way, mixes with combined mineral admixtures (GGBDMERHA series) showed better resistance up to 5% RHA. GGBDMERHA1 had low RCPT values and less permeability. But when the RHA content went up to more than 10%, the water absorption and RCPT values went up because the material became more porous and needed more water. All of the modified mixes did better than the control mix in tests for resistance to acid and sulfate. GGBDME2 and GGBDMERHA1 lost less weight, which means they were better at resisting chemical attacks. But more RHA made things substandard. In general, the results show that GGBS and metakaolin make things last longer, while too much RHA makes things work substandard. [26] Figures 10, 11, 12, and 13 illustrate the percentage of water absorption, RCPT results, percentage weight loss under acid resistance, and percentage weight loss under sulphate attack, respectively.

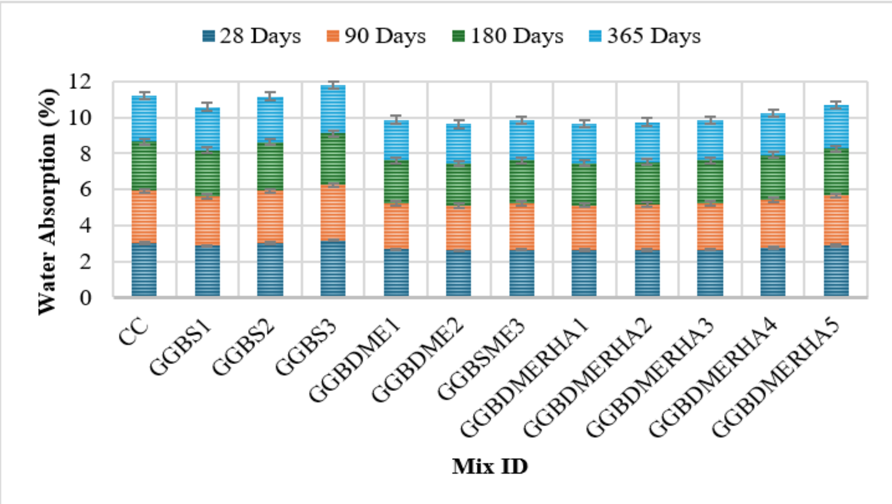

Figure 10. Percentage of water absorption

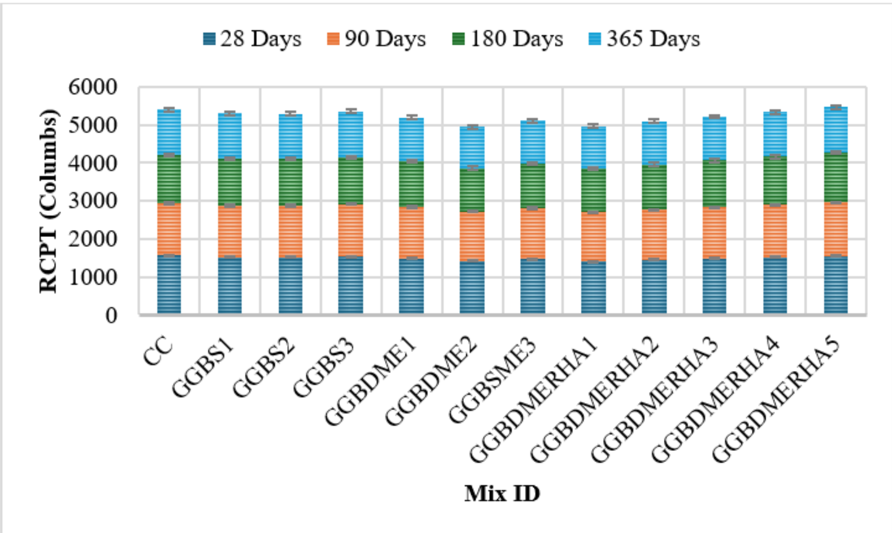

Figure 11. RCPT

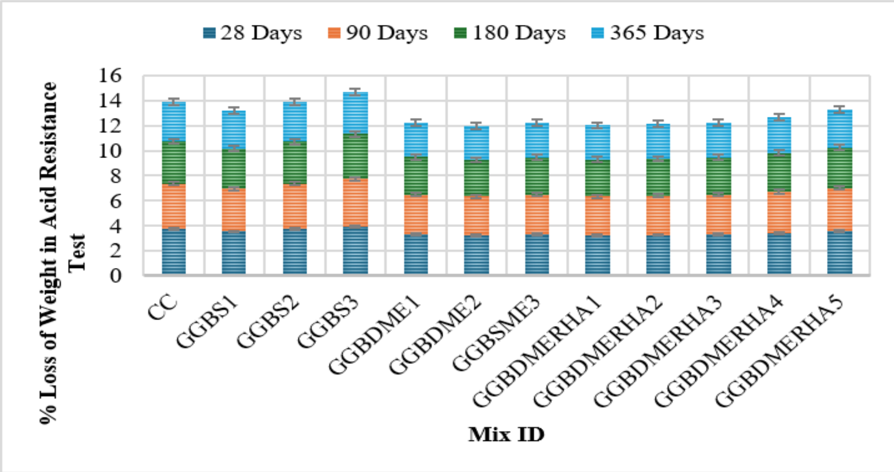

Figure 12. Weight Loss Percentage under Acid Exposure

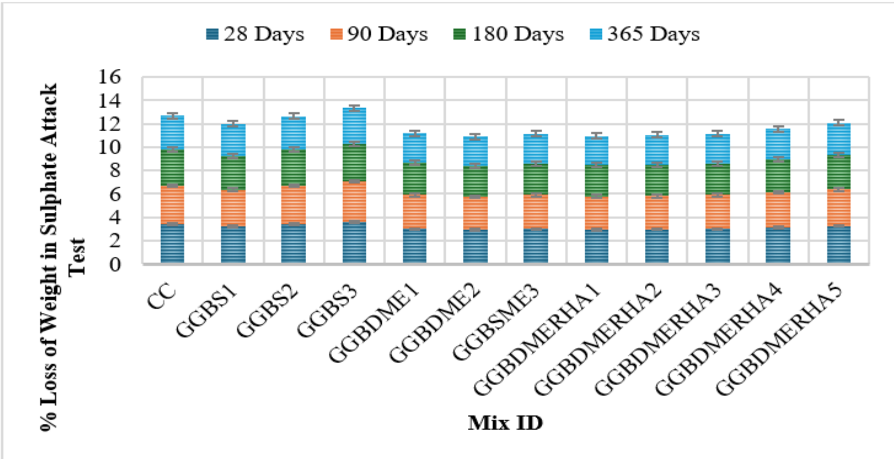

Figure 13. Weight Loss Percentage under Sulphate Attack

4.4. Microstructural Analysis – SEM Analysis

It was observed from the SEM test that there were distinct differences between the two types of concrete. First, there was noticeable porosity in the control concrete (CC). Moreover, voids and micro-cracking were evident in addition to a loose packing of hydrated materials. It was also found that calcium hydroxide crystals and hydrates of cement could be found in the matrix, showing that complete hydration had not taken place. However, when it came to the mixes that included GGBS (GGBS2), the microstructure became denser along with the presence of more C-S-H gel formation.

The presence of metakaolin in GGBDME2 improved the microstructure through the formation of an even and dense microstructure. Due to the pozzolonic activity of metakaolin, there was the consumption of $Ca(OH)^2$ and formation of more C–S–H gels, thus decreasing the porosity and increasing interfacial bonding. The combination of effects of GGBS, metakaolin, and RHA in the ternary composite GGBDMERHA2 led to a well-refined microstructure with no visible pores. There were however few porous areas as a result of the high water requirement and the fineness of RHA. Overall, mineral admixtures were seen to enhance microstructural refinement, hence improving on its properties [27, 28].

5. CONCLUSION

The current research was concerned about examining the effects of GGBS, metakaolin, and RHA on properties of M40 grade concrete. It was found out that the effect of using mineral admixtures in concrete is tremendous. Considering fresh properties, it could be noted that GGBS helped increase workability of concrete due to its smooth nature, whereas metakaolin and RHA affected the flow of fresh concrete negatively owing to smaller particle size and higher water demand.

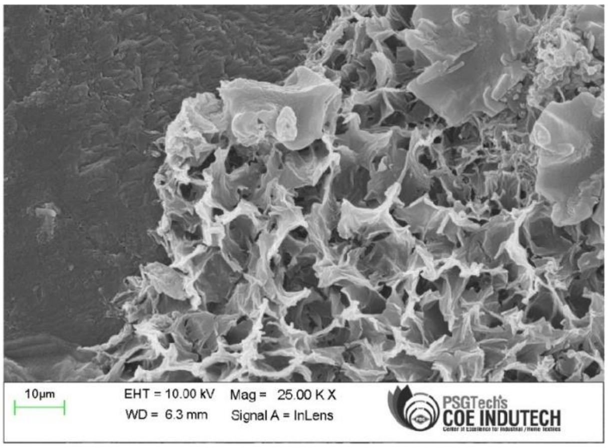

Figure 14. SEM images of CC

Figures 14 to 17 show the SEM micrographs of the CC, GGBS2, GGBDME2 and GGBDMERHA2 mix.

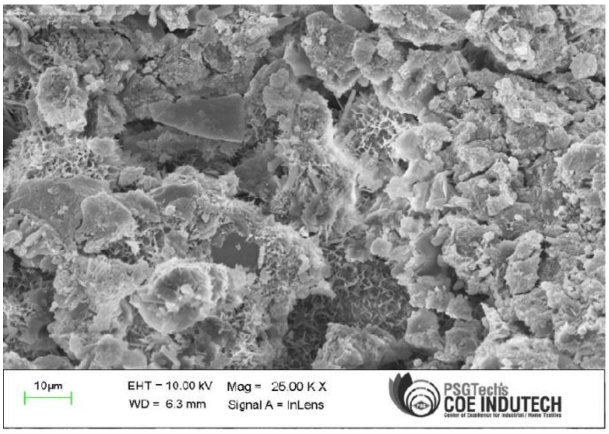

Figure 15. SEM images of GGBS2

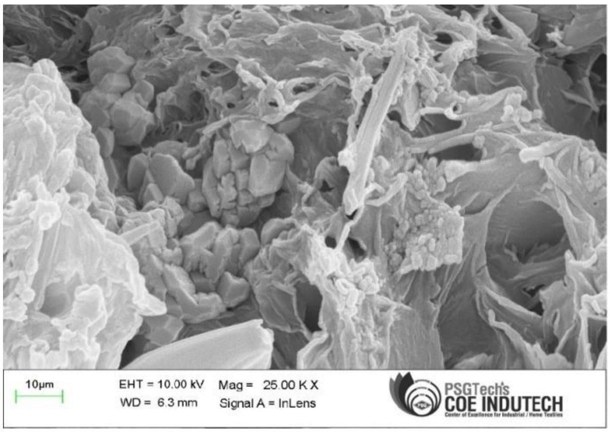

Figure 16. SEM images of GGBDME2

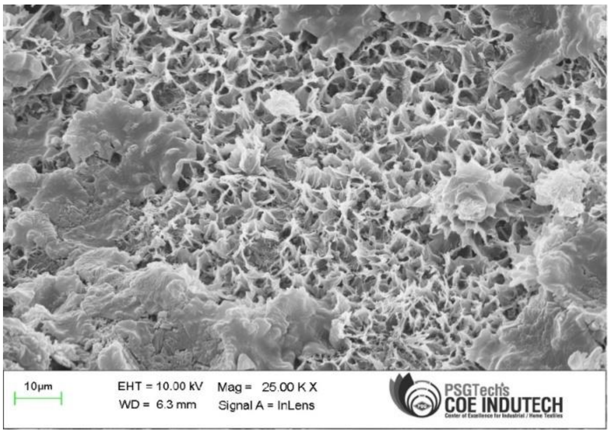

Figure 17. SEM images of GGBDMERHA2

Nonetheless, all samples had acceptable performance levels. Concerning mechanical properties, the presence of GGBS helped to attain good compressive strength in the long run due to its latent hydraulic properties. Metakaolin played an important role in increasing compressive strength both in the initial and subsequent stages. Maximum compressive strength could be achieved in mixes having GGBS and metakaolin in ratios of 20% and 10%, respectively. Rice husk ash up to 5-10% helped increase compressive strength but beyond that compressive strength decreased. Results from durability tests revealed that mineral admixtures caused a considerable decrease in water absorption and chloride permeability. The minimum RCPT and water absorption values were obtained for mixes with GGBS and metakaolin, implying increased resistance to aggressive environments. Weight losses were reduced in acid and sulfate resistance tests, revealing that the mixes were resistant to chemicals. SEM results demonstrated that the mixes with mineral admixtures produced a dense and tight microstructure with a reduction in pore formation. Further scope of this research work involves exploring the cost analysis of these mixes.

6. REFERENCES

[1] A. N. Swaminathen, C. V. Kumar, S. R. Ravi, S. Debnath (2021) Evaluation of strength and durability assessment for the impact of Rice Husk ash and Metakaolin at High Performance Concrete mixes. *Materials Today: Proceedings,* 47, 4584-4591. https://doi.org/10.1016/j.matpr.2021.05.449

[2] A. S. Gill, R. Siddique (2018) Durability properties of self-compacting concrete incorporating metakaolin and rice husk ash. *Construction and Building Materials,* 176: 323-332. https://doi.org/10.1016/j.conbuildmat.2018.05.054

[3] A. S. Gill, R. Siddique (2017) Strength and micro-structural properties of self-compacting concrete containing metakaolin and rice husk ash. *Construction and Building Materials,* 157, 51-64.

https://doi.org/10.1016/j.conbuildmat.2017.09.088

[4] V. Kannan (2018) Strength and durability performance of self compacting concrete containing self-combusted rice husk ash and metakaolin. *Construction and Building Materials,* 160, 169-179. https://doi.org/10.1016/j.conbuildmat.2017.11.043

[5] S. S. Pradhan, U. Mishra, S. K. Biswal, S. Pramanik, P. Jangra, F. Aslani (2024) Effects of rice husk ash on strength and durability performance of slag-based alkali-activated concrete. *Structural Concrete,* 25(4), 2839-2854. https://doi.org/10.1002/suco.202300173

[6] A. Sharma, S. A. A. Gupta (2021) Study on the Strength Aspects of Concrete with Metakaolin, GGBFS and Rice Husk Ash as Partial Replacement of OPC. In *IOP Conference Series: Earth and Environmental Science*, 889(1), 012072. DOI 10.1088/1755-1315/889/1/012072

[7] Y. Y. Lim, T. M. Pham (2021) Influence of Portland cement on performance of fine rice husk ash geopolymer concrete: Strength and permeability properties. *Construction and Building Materials,*300, 124321. https://doi.org/10.1016/j.conbuildmat.2021.124321

[8] P. Damodaran, Y. Mayilsamy (2025) Strength and characterization studies on nano-silica and steel fibre reinforced bacterial concrete: An eco-friendly and sustainable approach. *Res. Eng. Struct. Mater*. 11(6), 2837-2848. http://dx.doi.org/10.17515/resm2025-652ma0202rs

[9] P.S. Sajeev, Vijay Shankar GiriRajagopal, and Naveen Arasu, (2025) Investigation of concrete durability enhancement using supplementary cementitious materials, *MethodsX*: 15, 103527,https://doi.org/10.1016/j.mex.2025.103527

[10] V. Kannan and K. Ganesan (2014) Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin. *Construction and Building Materials,* 51, 225-234. https://doi.org/10.1016/j.conbuildmat.2013.10.050

[11] T. Ali, QureshiMZ, Inam I, Kahla NB, Ahmed H, Ajwad A, Adnan M (2025) Sustainable concrete production through the integration of waste foundry sand, fly ash, silica fume and metakaolin. *Scientific Reports* 15(1), 27512. https://doi.org/10.1038/s41598-025-13277-9

[12] A. A. Al-Naghi, N. Ghazouani, A. Selmi, Y. Alashker, A. Raza (2025) Combined effects of elevated temperature, sulfates and chlorides on performance of fly ash and metakaolin-based recycled aggregate geopolymer concrete. *Journal of Building Engineering,* 99, 111561. https://doi.org/10.1016/j.jobe.2024.111561

[13] H. La, M. Uddin, T. Nguyen (2025) Reliable inverse optimization of rice husk ash concrete via copula-based design spaces and conformal quantiles urrogates. *Expert Systems with Applications,* 301, 130582. https://doi.org/10.1016/j.eswa.2025.130582

[14] Z. Guo, Z. Chen, X. Yang, L. Zhang, C. Li, C. He, W. Xu (2025) The influence of rice husk ash incorporation on the properties of cement-based materials. *Materials*, 18 (2), 460. https://doi.org/10.3390/ma18020460

[15] S. Srinivasan, N. Muthusamy, & N. A. Anbarasu, (2024) The structural performance of fiber-reinforced concrete beams with nanosilica, Matéria (Rio de Janeiro), 29(3), e20240194. https://doi.org/10.1590/1517-7076-RMAT-2024-0194

[16] N. Concha, J. M. Bayhonan, J. Paano, A. D. Sultan, M. S. Tunay (2025) Parametric Analysis and Machine Learning Model for Compressive Strength of Rice Husk Ash Concrete. *Archives of Computational Methods in Engineering,*p. 1-30. https://doi.org/10.1007/s11831-025-10479-2

[17] T. N. Durai, S. Kandasamy, A. R. Christabel (2025) Enhanced mechanical properties in green concrete through innovative blends of GGBFS, alccofine, and metakaolin. *Hybrid Advances,* 11, 100520. https://doi.org/10.1016/j.hybadv.2025.100520

[18] Y. Jing, J. C. Lee, W. C. Moon, J. L. Ng, M. K. Yew, Y. Jin (2025) Durability and environmental evaluation of rice husk ash sustainable concrete containing carbon nanotubes. *Scientific Reports*, 15(1), 4352. https://doi.org/10.1038/s41598-025-88927-z

[19] M. J. Geu, Y. Zhuge, X. Ma, T. M. Pham (2026) Systematic review of physical, mechanical and durability performances of metakaolin concrete, *Applied Clay Science,* 279, 108048. https://doi.org/10.1016/j.clay.2025.108048

[20] N. Raveendran, V. Krishnan (2025) Engineering performance and environmental assessment of sustainable concrete incorporating nano silica and metakaolin as cementitious materials, *Scientific reports,* 15(1), 1482. https://doi.org/10.1038/s41598-025-85358-8

[21] Y. M. Abbas, A. Alsaif (2025) Explicit gradient boosting machine for accurate compressive strength prediction of metakaolin-based geopolymer concrete: feature importance and optimization, *Journal of Materials Research and Technology*, 38, 2299-2314, https://doi.org/10.1016/j.jmrt.2025.08.064

[22] B. Zhang, Y. Zhou, H. Gong, Y. Liang, D. Liu, Y. Wang, Y. Ma, Q. Zhang, T. Ji (2025) Effect of curing regime on ultra-high performance concrete containing metakaolin and magnesium oxide. *Construction and Building Materials,* 490, 142388. https://doi.org/10.1016/j.conbuildmat.2025.142388

[23] Annamalai, Kumar, Naveen ArasuAnbarasu, Balaji Ponraj Govindarajan, and Sujatha Sivarethinamohan, (2025) Sustainable concrete: integrating environmentally friendly materials for environmentally friendly construction, *Matéria (Rio de Janeiro)* 30,e20250239. https://doi.org/10.1590/1517-7076-RMAT-2025-0239

[24] S. Khan S, M. Parveez, M. A. Tantray (2025) Metakaolin-infused concrete for sustainable and durable building rehabilitation. *Journal of Building Pathology and Rehabilitation,* 10, 1: 66. https://doi.org/10.1007/s41024-025-00578-9

[25] U.U.Imoh, M.Habashneh, S.C.Kaine, A.J.Babafemi, R.Hassan, M.MovahediRad (2025) Metakaolin-Enhanced Laterite Rock Aggregate Concrete: Strength Optimization and Sustainable Cement Replacement, *Buildings,* 15(24),4553.https://doi.org/10.3390/buildings15244553

[26] L. Zhu, Z. Zhao, Y. Zhao, Y. Xiang, X. Guan (2025) Study on the enhancement of thixotropic properties of steel slag-based digital concrete by metakaolin, *Case Studies in Construction Materials,* 22,e04293. https://doi.org/10.1016/j.cscm.2025.e04293

[27] K. Hasan, H. Khatun, R. Mazumder, R. P. Jaya, F. M. Yahaya (2025) Performance of sustainable ternary blended concrete using rice husk Ash and Metakaolin as partial cement substitutes, *Innovative Infrastructure Solutions,* 10(11), 528. https://doi.org/10.1007/s41062-025-02328-9

[28] N. B. Lima, M. Pontes, D. Silva, R. C. Manta, B. D.Teti, H. C. Nascimento, L. B. Santos, N. B. Lima (2025) Evaluation of probability distributions in the study of characteristic compressive strength of metakaolin concrete blocks, *Ambiente Construído,* 25,e138069. https://doi.org/10.1590/s1678-86212025000100806

IZVOD

RAZVOJ I KARAKTERIZACIJA PERFORMANSI EKOLOŠKI PRIHVATLJIVOG TERNARNOG MEŠANOG BETONA KORIŠĆENJEM INDUSTRIJSKIH I POLJOPRIVREDNIH OTPADNIH MATERIJALA

Ovo trenutno istraživanje pokušava da istraži uticaj mineralnih dodataka poput pepela pirinčane ljuske (RHA), metakaolina i GGBFS na fizička, mehanička i trajna ponašanja betona klase M40. Različite mešavine betona su pripremljene korišćenjem delimične zamene GGBS-a, metakaolina i RHA umesto cementa. Sprovedeni su testovi sleganja, test L-kutije, V-levka, J-prstena i U-kutije radi procene novih svojstava. Nakon različitih perioda očvršćavanja, procenjena su mehanička svojstva poput čvrstoće na savijanje, zatezne čvrstoće na cepanje i čvrstoće na pritisak. Otkriveno je da dodavanje metakaolina poboljšava ranu čvrstoću i gustinu mikrostrukture, dok upotreba GGBS-a poboljšava obradivost i čvrstoću. Utvrđeno je da je kombinacija 10% metakaolina i 20% GGBS-a najefikasnija. Uključivanje RHA povećalo je performanse do 5-10%, ali je smanjilo čvrstoću i obradivost za više od 10%. U analizi trajnosti primećena je smanjena brzina apsorpcije vode, otpornost na napad hlorida i kiselo-sulfatnu sredinu.

Ključne reči: *GGBS, metakaolin, pepeo pirinčane ljuske.*

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