



International Journal of Artificial Intelligence and Machine Learning

Publisher's Home Page: <https://www.svedbergopen.com/>



Research Paper

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Enhancing Mechanical and Durability Properties of Concrete Through Partial Replacement of Cement With GGBS and Metakaolin

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Abstract

The effort toward the use of sustainable supplementary cementitious materials such as GGBS and MK has gained momentum on account of increasing apprehension with regard to energy consumption and carbon dioxide emission [1]. In this study, a total number of five concrete mixes were prepared-one control mix was prepared with 100% ordinary Portland cement, and four blended mixes were prepared with a constant 30% GGBS and MK replacement levels of 5%, 7.5%, 10%, and 12.5% [2]. The mixes were prepared for M40 grade concrete according to IS 10262:2019, maintaining a fixed W/B ratio of 0.42. The mechanical strength and durability properties of the concrete specimens were monitored after 7, 28, and 56 days of curing under aggressive environments with H_2SO_4 , Na_2SO_4 , and $MgCl_2$ [3], [4]. Results indicated that the concretes produced using GGBS and MK in combination imparted the best performance. The high pozzolanic reactivity of MK accelerates strength gain at the early age, whereas the latent hydraulic nature of GGBS tends to increase strength continuously at later ages by improving ITZ [5]. These two mineral admixtures have interactively performed since the maximum compressive, split tensile, and flexural strengths were achieved within the range of 7.5% and 10% MK replacement. Such synergy enhances resistance against chemical attack through the formation of a denser and more homogeneous microstructure [6]. However, increasing the MK content up to 12.5% leads to a slightly deteriorated performance, which is caused by the surface area-induced increase in water consumption and loss of workability [7]. According to the experiment results, concrete containing 30% GGBS and 7.5% to 10% MK provided the best possible balance among durability, mechanical strength, and environmental sustainability [8]. This blend is hence an excellent formulation for high-performance green concrete applications.

Keywords: M40 grade concrete, ternary blended concrete, ground granulated blast furnace slag (GGBS), metakaolin (MK), sustainable high-performance concrete, and durability properties.

Introduction

The above two mineral admixtures have been acting in tandem since the highest values of compressive, split tension, and flexural strengths were found, as shown in a range between 7.5% and 10% of the addition of MK. The performance in resisting chemical attack is improved, thanks to the denser homogeneous microstructure ensured by the interaction between the two admixtures in the cement paste [6]. Still on the interaction issue, it should however be noted that the addition of 12.5% of the admixture results in a slightly lower performance, a factor of the increase in the water demand due to the increased surface area, as indicated in another study observing the effects of the addition of the admixture on concrete involving the addition of 30% GGBS and 7.5%, 10%, and 12.5% of the admixture to the cement paste, as the results indicate the optimized balance of sustainability, strength, and durability of the concrete composition. Sustainable construction approaches, which include techniques intended to decrease the environmental impacts of building components without compromising performance characteristics, have become essential with the rising environmental concerns. The most effective way of achieving sustainability in concretes involves using a fraction of alternative cementitious binder substitutes of cement. [13] Burning fossil fuels, calcination of limestone, resource depletion, large amounts of energy consumption, particle release, and environmental upsets resulting from quarrying limestone for making cement are considered to be responsible for the environmental impacts of making cement. Researchers and engineers are working steadfastly on the incorporation of secondary materials and industrial byproducts through partial cement substitution to reduce these effects. Such a technique has a dual role: it reduces carbon emissions from manufacture, while at the same time, it provides the possibility of using industrial waste efficiently, which reduces the quantum of trash reaching landfills. Moreover, the main hydration product, calcium silicate hydrate gel (C-S-H), is formed when finely divided ingredients with pozzolanic or latent hydraulic properties react pozzolanically with calcium hydroxide, which forms from the hydration of cement, thereby enhancing strength and durability. [14] Other advantages of using SCMs include reduced

cement consumption, better resistance to adverse environmental conditions [15], new concrete performance, and better strength development with time. Fly ash, silica fume, metakaolin, rice husk ash, and GGBS are examples of some regularly used supplemental binders and SCMs employed commonly. These materials, when their inclusion of GGBS and metakaolin are incorporated with two of them, have attracted a great deal of interest due to their high reactivity and good performance when used either alone or blended in combinations. [18]. Experiments on blended concrete mixes with varying metakaolin percentages of 5%, 7.5%, 10%, and 12.5% and a fixed replacement of cement with GGBS at 30% demonstrated that the mix containing 30% GGBS and 7.5% metakaolin yielded the best performance. [19] Strength was marginally lower for higher metakaolin replacements at 10% and 12.5%. This was primarily as a consequence of higher water consumption and loss of workability, which highlighted the importance of optimum proportioning in blended cementitious systems. [20]

2. Methodology

A methodical experimental study was the mechanical characteristics and longevity of M40 concrete at varying degrees of sustainable binder inclusion. In order to enable trustworthy comparison and precise interpretation of data, the experimental program was created to guarantee uniformity in mix design, specimen preparation, curing conditions, and testing processes.

2.1 Materials

Regular Portland cement that met the applicable Indian Standard requirements served as the primary binder in this inquiry. [1] metakaolin (MK) and ground granulated blast furnace slag (GGBS) were utilized due to additional cement-based binder materials to partially replace cement. While locally available natural river sand that satisfied acceptable grading standards was used as fine aggregate, crushed angular coarse aggregates with the proper nominal maximum size were selected in accordance with Indian Standards. In addition to one control mix composed completely of cement, the four blended mixes in the experimental program included varying proportions of metakaolin (5%, 7.5%, 10%, and 12.5% by weight of cement) and a constant 30% replacement of ground granulated blast furnace slag (GGBS) as a supplementary binder component. [11] Throughout study, potable water that was pure and appropriate for using during concrete mixing and subsequent curing.



Fig.1.1: GGBS



Fig.1.2: Metakaolin



Fig.1.3: Cement



Fig.1.4: Coarse Aggregate



Fig.1.5: Fine Aggregate

2.2 Mx Proportioning

Following IS 10262's guidelines, the mix proportioning for M40 grade concrete was completed. To attain the desired mean strength, a control mix was created. After that, modified concrete mixes were made by substituting GGBS and metakaolin for some of the cement at the chosen replacement levels, all the while keeping the water-to-binder ratio constant. To guarantee consistency and accurate comparison of outcomes, all concrete mixtures were prepared, proportioned, and cast using the same methods.

Table 1: Mix Proportioning

Mix ID	Cement	GGBS	Metakaolin
M1	100%	-	-
M2	65%	30%	5%
M3	62.5%	30%	7.5%
M4	60%	30%	10%
M5	57.5%	30%	12.5%

2.3 Specimen Preparation and Curing

To attain the desired mean strength, the M40 concrete mix was created in compliance with IS 10262. While keeping the water-binder ratio constant, a control mix and modified mixes were created using ground granulate blast furnace slag (GGBS) and metakaolin (MK) by replacing. To guarantee uniformity, the same processes were used to create every combination. Prism, cylinder, and standard cube specimens prepared for flexural, tensile strength, and compressive stress capacity tests, respectively. Demoulding was carried out after 24 hours of casting, then allowed to undergo at room temperature for a curing duration of 28 and 56 days before testing.


Fig 2.1: Slump Test

Fig 2.2: Casting

Fig 2.4: Specimens

Fig 2.4: Curing

2.4 Mechanical Properties Tests

Cube specimens' compressive strength was assessed at 28 and 56 days in compliance with IS 516. Cylindrical specimens were used to measure tensile splitting strength was evaluated in compliance with as IS 5816, and prism specimens were used to measure flexural strength under two-point loading circumstances using conventional testing methods. For every concrete mix, the average values of the test findings were published.


Fig.3.1: Compression Test

Fig.3.2: Splitting Test


Fig 3.3: Flexural Test

2.5 Durability Properties

In order to assess the durability performance of concrete mixes, chemical assault experiments were conducted. To test for acid resistance, specimens were submerged in sulfuric acid (H_2SO_4); to test for chloride and sulphate resistance, respectively, magnesium chloride ($MgCl_2$) and sodium sulphate (Na_2SO_4) solutions were utilized. For each concrete mix, the durability performance was calculated using changes in mass and residual strength after the specified exposure period, the average findings were given.

**Fig.4.1:** Acid Solutions**Fig 4.2:** Acid solutions mixing**Fig 4.3:** Acid Curing**Fig.4.4:** Specimens after curing

2.6 Data Analysis

The mean values obtained for each concrete mix were used to examine the test findings. Strength development brought about by the addition of GGBS and Metakaolin was assessed by comparing mechanical characteristics at 28 and 56 days with the control mix. The specimen's durability behaviour was assessed by testing their residual strength following exposure to acid, chloride, and sulphate environments. All of the combinations were evaluated to determine the optimal replacement level that showed superior strength and durability performance.

3. Literature review

Concrete possesses mechanical characteristics of performance that will greatly enhance by partially substituting cement with additional cementitious materials such as GGBS and Metakaolin, as revealed by prior research. Since GGBS has the latent hydraulic properties of improving strength related properties and chemical attacks, metakaolin with its exceptional pozzolanic characteristics offers the benefits of improving strength development along with a refined pore structure. The addition of GGBS and Metakaolin improves the durability of concrete with the benefits of acid, chloride, and sulphate attack resistance and reduction of permeability.

The effective role of metakaolin modified concrete that acts as a reactive pozzolanic material, there by showing promising enhancements in mechanical properties and durability due to improvements in pore structure and the production of secondary C-S-H products, was reported from early studies. The study done by Joshaghani et al. (2017) indicated that the use of metakaolin significantly increased the compressive strength of the concrete mixture, thereby reducing the cement permeability and chloride penetration. At reduced water to binder ratios, the percentage of an overall 12.5% metakaolin is required in such mixes. Kaur and Sran (2016) have conducted studies on the enhancement of compressive strength with increased amounts of metakaolin. 9% Metakaolin was preferred for M30 grade concrete.

Moreover, the viability of GGBS to enhance the mechanical and durability properties of concrete was shown by concurrent studies. In addition, Satyanarayana and Chaitanya (2019) observed that concretes lubricated by GGBS were more resistant to acid and sulfate attacks compared to metakaolin-based concretes. This shows the latent hydraulic activity of GGBS under severe conditions. Another study conducted by Naveena and Anantha Lakshmi (2017) supported the practicability of GGBS to produce sustainable concretes by confirming its ability to enhance

compressive strength and promote sufficient workability when it replaces cement to some extent.

Since GGBS and metakaolin have similar hydration characteristics, their combined effects have been extensively studied by scientists. By optimizing a mixture containing 15% GGBS and 15% metakaolin, Sanjeev and Sampath Kumar Reddy (2019) demonstrated that by using M40 grade fiber reinforcement, noticeable improvement may be achieved in terms of compressive, split tensioning properties, and durability. In a study where a ternary mixture was optimized to include 15% metakaolin and 9% GGBS to achieve superior mechanical properties, Saeed and Pasha (2022) underlined the need to achieve balanced proportions to mitigate reduced workability.

Dani and Shobha (2022) report better mechanical properties for the M40 grade of concrete at the optimum combination of 10% GGBS and 10% metakaolin replacement, which again reflects the synergism effect. From the review work by Fathima and Anjaly (2020) in the area of SCM research, it can be seen that the optimum replacement was found to be within the range of 10-15% for metakaolin and 30-50% for GGBS, reflecting better performance for combination SCM concretes compared to their single admixture counterparts.

Recently, the above findings have also been implicated to encompass geopolymer and high-performance concrete systems. In the case of slag-based alkali activators, Elmaasrawy et al. (2025) investigated and proved the ability of metakaolin systems, which have exhibited an exceeding compressive strength of 110 MPa due to high-density aluminosilicate gel formation. Padmakar et al. (2017) conducted experiments to prove the enhanced mechanical strength of metakaolin-GGBS geopolymer concretes compared to traditional OPC concretes, where Portland cement was not used. Chen et al. (2021) and Amorim Júnior et al. (2021) carried out durability tests and proved the enhanced ability of the metakaolin-GGBS.

Limited specific studies have been carried out on M40-grade concrete subjected to controlled levels of acid, chloride, and sulfate environments, focusing on the residual mechanical properties of the concrete at later curing ages, though a substantial amount of research has already been carried out, thus proving the specific advantages of the use of GGBS and metakaolin individually or in combination. Hence, an attempt is made in the current study to fill the gap in available knowledge by evaluating the properties of M40 concrete using optimized combinations of GGBS and metakaolin in a severe chemical environment.

4. Results and Discussion

4.1 Compressive Strength

Both 28, and 56days compression strength performance findings show the impact of mix change. The compression strength rise 47.185 strength values (MPa) for M1 to a maximum of 52.698 MPa for Mix M3 after 28 days, demonstrating better particle packing and early-age matrix densification as a result of efficient pozzolanic activity. Mixes M4 (50.962 MPa) and M5 (49.985 MPa) showed a minor loss in strength, indicating dilution effects at higher replacement levels.

Table.2: Compressive Strength of Concrete Mixes

Mix-ID	28 days (MPa)	56 days (MPa)
M1	47.185	52.292
M2	49.333	54.222
M3	52.698	56.814
M4	50.962	57.592
M5	49.985	55.894

All mixes continued to build strength at 56 days. After Mix M3 (56.814 MPa) and Mix M5 (55.894 MPa), Mix M4 had the highest compressive strength (57.592 MPa). Delayed pozzolanic reactions, which cause pore refinement and this improvement is attributed to the increase formation of secondary calcium silicate hydrate (C-S-H) gel, are responsible for the improved later-age performance. Mix M1 demonstrated satisfactory structural performance at later ages despite exhibiting relatively reduced strength.

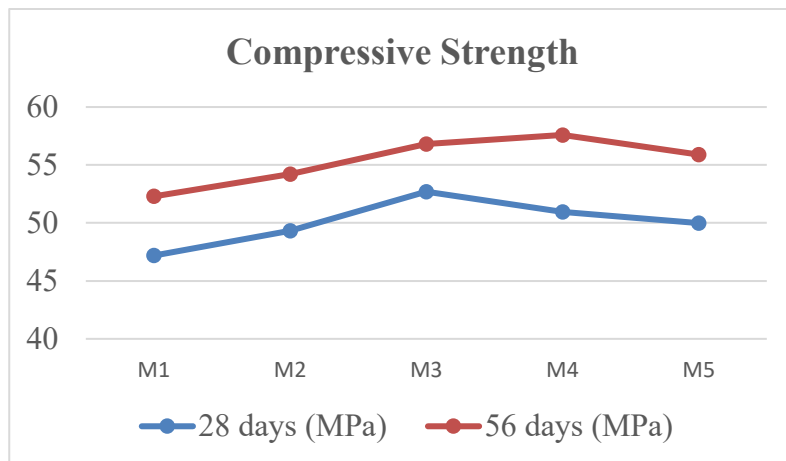


Fig.5: Compressive strength development at 28days vs 56 days

4.2 Split Tensile Strength

Variation in the mix proportion appeared to have a significant influence on tensile properties in the curing levels of the concrete. The results from the 28 days indicate that there is a gradual increase in the split tensile strength from 3.72 MPa in M1 to a maximum of 4.16 MPa in M3, indicating enhanced interfacial bond between the matrix particles. Mixes M4 (4.05 MPa) and M5 (3.90 MPa) recorded a decrease in tensile strength.

Table.3: Splitting Tensile Test Results at 28, and 56 days

Mix-ID	28 days (MPa)	56 days (MPa)
M1	3.72	4.55
M2	3.88	4.68
M3	4.16	4.82
M4	4.05	4.96
M5	3.9	4.78

For all mixtures, the tensile resistance kept increasing up to 56 days. Mix M4 showed the maximum tensile strength at 4.96 MPa, followed by Mix M3 (4.82 MPa) and Mix M5 (4.78 MPa). The delayed pozzolanic reactions, which cause matrix densification, improvement in crack-bridging capacity, and modification of the interfacial microstructure leading to improvement in stress transfer, are responsible for improvement in the tensile strength at later ages. Mix M1 recorded values that were comparatively lower, though it showed good tensile performance throughout time.

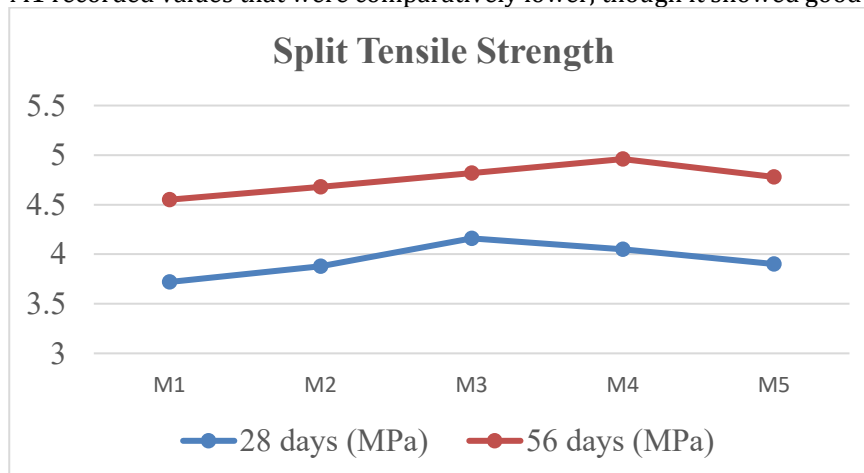


Fig.6: Split Tensile Strength Test at 28days vs 56 days

4.3 Flexural Strength

The addition of supplementary cementitious materials led to an improvement in the flexural performance of all mixtures adjusted at both curing ages compared to the reference mixture. An increase in flexural strength from 4.66 MPa for Mix M1 to 5.12 MPa for Mix M3 was recorded at 28 days, indicating an improvement in the load-carrying ability and tensile stress distribution at the concrete matrix. Mixes M4 and M5, with a slightly reduced flexural

strength of 4.96 MPa and 4.80 MPa, respectively, exhibited a decline beyond this level, insinuating that higher replacement levels did not contribute proportionately to early-age flexural performance.

Table.4: Flexural Performance of Concrete mixes

Mix ID	28 days	56 days
M1	4.66	5.9
M2	4.82	6.17
M3	5.12	6.45
M4	4.96	6.56
M5	4.8	6.3

Resistance to development of capacity was observed more prominently in all the mixes at 56 days. The maximum value was recorded by M4 Mix with 6.56 MPa, followed by 6.45 MPa recorded by Mix M3 and 6.30 MPa recorded by Mix M5. The pozzolanic reactions ensured the performance of the interfacial transition zone over longer durations; compactness of matrix was observed in Mix M1's flexural strength value at 56 days, though the value was recorded on the lower side.

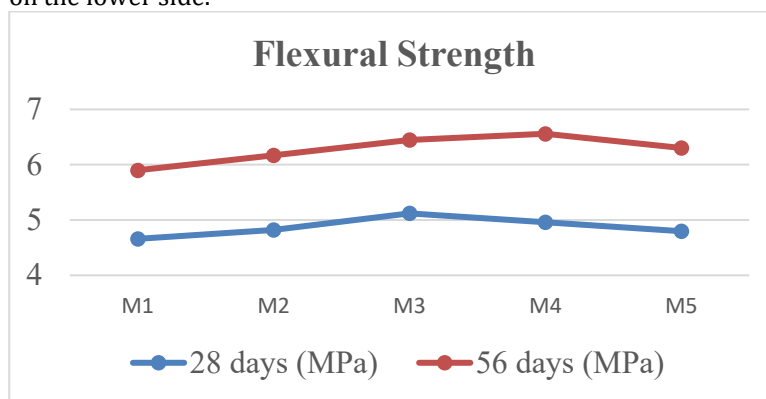


Fig.7: Flexural Strength Test at 28days vs 56 days

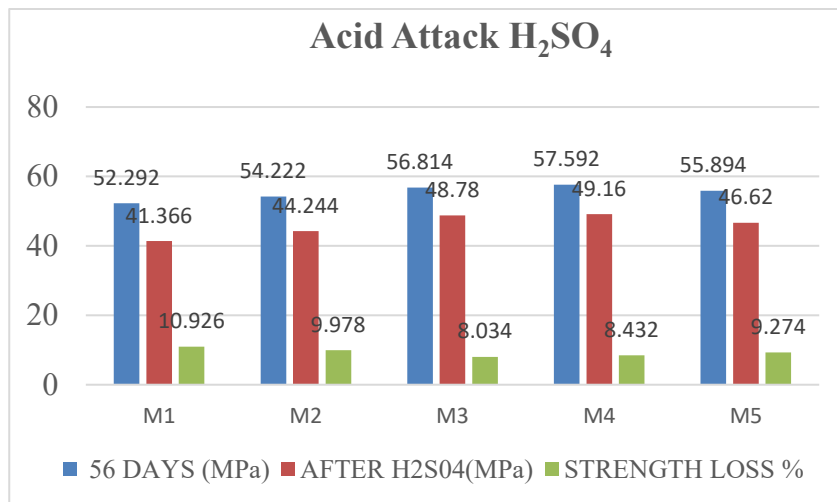
4.4 Acid Attack Resistance

All concrete mixtures presented a distinguishable degradation in strength performance under acid attack. The maximum degradation was observed for the reference mix, M1, which suffered from strength loss of 10.926% from the strength of 52.292 MPa after 56 days to 41.366 MPa after H_2SO_4 attack. Similarly, though there was comparatively better performance by the mixes with incorporated materials than the nominal mixes, the FBC incorporated mixes M2 and M5 suffered strength losses of 9.978% and 9.274%, respectively, indicating their improved resistance to acid attack.

Table.5: Acid Attack Resistance (4% H_2SO_4)

Mix Id	56 Days (MPa)	After H_2SO_4 (MPa)	Strength Loss %
M1	52.292	41.366	10.926
M2	54.222	44.244	9.978
M3	56.814	48.78	8.034
M4	57.592	49.16	8.432
M5	55.894	46.62	9.274

With the least amount of strength loss (8.034%) and a residual compressive strength of 48.780 MPa, Mix M3 was the most resistant to sulfuric acid assault among the modified mixes. Mix M4 also did well, with a post-exposure strength of 49.160 MPa and a strength loss of 8.432%. These mixtures' increased acid resistance can be explained by their denser microstructure and decreased calcium hydroxide availability as a result of pozzolanic reactions, which together prevent acid penetration and consequent material deterioration.


Fig.8: Acid Attack Resistance

4.5 Chloride Attack Resistance

The ability of concrete mixes to resist chemical attacks from magnesium chloride (MgCl₂) was evaluated by comparing the compressive strengths of the mixes at 56 days with the residual strength after the chemical exposure. For nominal mix M1, it was observed that it slightly loses strength from 52.292 MPa to 51.072 MPa after the exposure, corresponding to a loss of 1.22%. Adjusted mixes M2 and M5 have losses of 1.18% and 1.12%, respectively, which are slightly smaller.

Table.6: Chloride Attack Resistance (4% MgCl₂)

MIX ID	56 DAYS (MPa)	AFTER MgCl ₂ (MPa)	STRENGTH LOSS %
M1	52.292	51.072	1.22
M2	54.222	53.042	1.18
M3	56.814	55.694	1.12
M4	57.592	56.542	1.05
M5	55.894	54.794	1.1

Mix M4, with a post-exposure compressive strength of 56.542 MPa and the least percentage of strength loss (1.05%), exhibited maximum resistance to the effects of magnesium chloride attack among the mixes. Although the enhanced performance of the modified mixes could be related to the matrix densification and reduced permeability brought about by the pozzolanic reactions; the minimal strength loss observed in all the mixes suggests that the attack from the MgCl₂ had minimal effects. Mix M3, with a residual strength of 55.694 MPa and a strength loss of 1.12%, exhibited good performance.

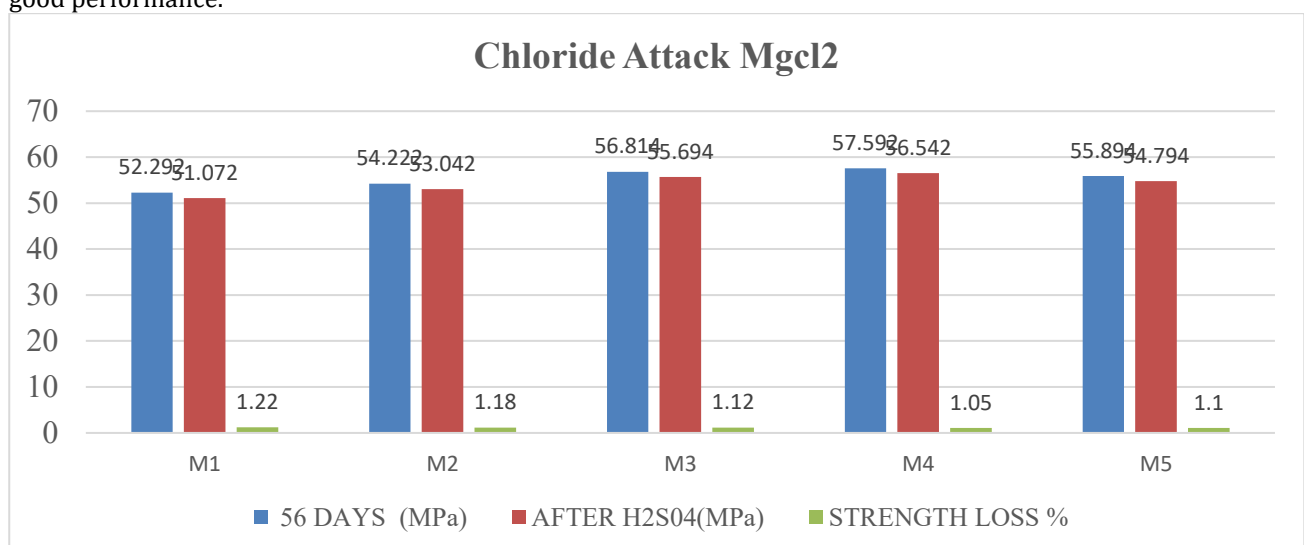


Fig.9: Chloride Attack Resistance

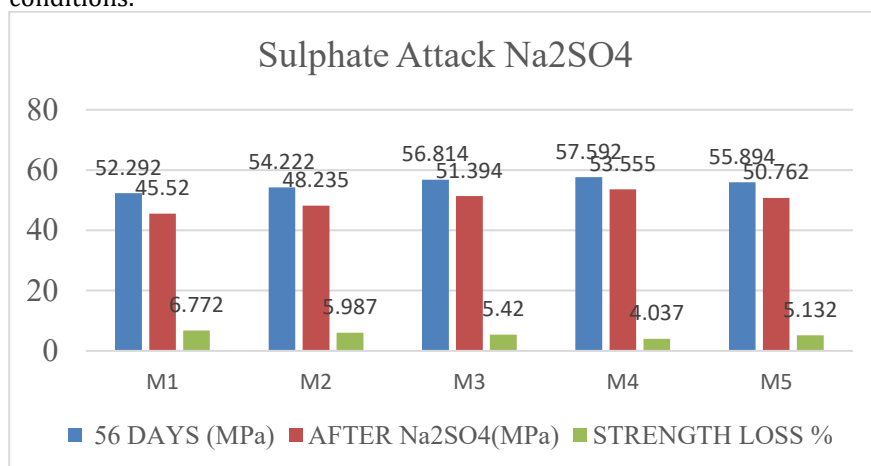
4.6 Sulphate Attack Resistance

Comparison of 56 days strength and residual strength after sulfate attack was made to assess the influence of sodium sulfate (Na_2SO_4) presence towards the mechanical strength of the material. While the compressive strength of the control mixture, denoted as M1, reduces from 52.292 MPa to 45.520 MPa, reflecting a reduction of 6.772%, the modified mixture revealed reduced loss in compressive strength, indicating resistance to decaying effects of sulfate.

Table.7: Sulphate Attack Resistance (4% Na_2SO_4)

MIX ID	56 DAYS (MPa)	AFTER Na_2SO_4 (MPa)	STRENGTH LOSS %
M1	52.292	45.52	6.772
M2	54.222	48.235	5.987
M3	56.814	51.394	5.42
M4	57.592	53.555	4.037
M5	55.894	50.762	5.132

Mix M4 was seen to possess superior sulfate resistance when compared to all adjusted mixes, where the residual compressive strength was maintained at 53.555 MPa. Additionally, the minimum strength loss was 4.037%. Mixes M3 and M5 had favorable results where their strength loss was 5.420% and 5.132%, respectively. As pozzolanic reactions restrain the entry of sulfate and minimize the expansive products obtained, it was clear that the mixes' performance was enhanced by their superior pore structure resulting from increased resistance to permeability. The results obtained verify that the superior binder system improves durability for concrete when subjected to sulfate conditions.


Fig.10: Sulphate Attack Resistance

5. Conclusion

From this testing, it was evident that concrete with a partial replacement has a significant impact upon the strength development and durability of grade M40 concrete. In terms of the strengths, tested under compression, tension, and bending in 28 and 56 days, it was evident that the mixes had better properties than the control mix. Experiments carried out with early-age concrete indicated that Mix M4 confirmed the highest compression, tension, and bending strengths at 56 days, while Mix M3 confirmed the highest values at 28 days. There was some reduction in early age strength with increased replacement mixtures; however, this effect was minor and did not bear any negative effects on long-term strength. When comparing these mixes to regular mixes for durability tests and comparing their resilience to chemical attacks, it was established that these mixes were more durable. Tests were carried out by exposing mixes to chlorides, which resulted in little degradation capacity for all mixes, although Mix M4 showed least degradation. Mixes M3 and M4 were more effective in resisting acid and sulfate exposures by reducing loss in strength. At 40-50%, there was an established ideal proportion for replacement considering durability and mechanical properties. According to the study, it was established that the proposed mix could be used as desired for structural purposes where more long-term performance and durability were required under harsh conditions.

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