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A COMPREHENSIVE STUDY ON THE INFLUENCE OF MINERAL ADMIXTURES AND POLYPROPYLENE FIBER ON THE STRENGTH AND SULFATE RESISTANCE OF SELF-COMPACTING CONCRETE

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ABSTRACT

The study focuses on the influence of mineral admixtures and polypropylene fiber on the strength and sulfate resistance of SCC. The research includes a comprehensive experimental study to assess the fresh and hardened properties of SCC mixtures with varying proportions of mineral admixtures and constant proportion of polypropylene fibers. The study included eight types of mix proportions, with the first four mixes excluding fibers and the remaining four incorporating 0.2% polypropylene fibers by the weight of the binder content. The water/binder ratio was determined to be 0.32 by weight. The control mixture included only OPC as the binder while the remaining mixtures incorporated Quaternary (OPC + FA + GGBS + SF) cementitious blends in which a proportion of 50% OPC was replaced with the mineral admixtures. The replacement ratios for both FA and GGBS were 10, 20, and 30% while those of SF of 10% by mass of total cementitious materials. The 15% strength of sodium sulfate solution is used for the durability test. The results showed that inclusion of fly ash improves; however, polypropylene fiber decreases the workability of concrete. The findings suggest that the addition of mineral admixtures such as FA, GGBS, and SF along with polypropylene fibers, can enhance the durability and strength of SCC against sulfate attack. The incorporation of SCM significantly enhances the resistance of concrete to sulfate attack. Substituting GGBS in quaternary mixes notably improves sulfate resistance and strength compared to the control. The results indicate that the addition of polypropylene fibers improves the resistance of concrete mixes to sodium sulfate exposure, leading to significant improvements in strength compared to mixes without fibers. Overall, the study emphasizes the benefits of using mineral admixtures and polypropylene fibers in SCC to enhance its strength, durability, and resistance to sulfate attack. And overall conclusions are drawn based on experimental results.

Keywords: Quaternary Blended Self Compacting Concrete (QBSCC), Silica Fume (SF), Ground Granulated Blast Furness Slag (GGBS), Fly Ash (FA), Polypropylene Fiber (PPF), Sodium Sulfate (Na_2SO_4), Supplementary Cementitious Materials (SCMs).

I. INTRODUCTION

Concrete is by far the most extensively consumed construction material, considering its cost efficiency, wide availability, load carrying capacity, and a variety of structural engineering applications. The evolution of concrete technology over recent decades has witnessed a significant paradigm shift, characterized by a departure from conventional formulations towards engineered materials tailored to meet the increasingly stringent demands of modern construction. This transformation has led to the emergence of SCC, a high-performance material distinguished by its exceptional flow ability and ability to autonomously fill formwork without the need for mechanical compaction.

The genesis of SCC can be traced back to the late 1980s, prompted by the need to address challenges such as inadequate compaction and segregation prevalent in traditional concrete practices. This imperative gained particular traction in regions like Japan, where concerns over the durability of concrete structures, exacerbated by premature deterioration, spurred researchers to seek innovative solutions. The seminal work of Professor Okamura and colleagues at the University of Tokyo marked a pivotal moment in the conceptualization of SCC, offering a solution to ensure uniform compaction and elevate construction quality amidst evolving industry constraints. However, the successful application of SCC requires careful consideration of material proportions and mix design [Okumura and Ozawa 1998] to ensure optimal performance.

Plentiful amount of wastes are generated from the thermal power plant and ferrosilicon industries. These wastes products caused numerous environmental issues to the environment against disposal. The issues can be overcome by the utilization of these products in concrete. The generated waste products from industries like FA, micro silica (MS) and GGBS could be effectively utilized at appropriate dosage towards the development of sustainable self-compacting concrete. One approach to enhancing the performance and durability of SCC is through the incorporation of mineral admixtures [H.N. Atahan et al. (2011); Adapala Sunny Suprakash et al. (2022)].

Development of modern civil engineering construction has generated an essential demand for new types of concretes which should possess improved qualities such as high-strength, toughness, and durability. The integration of mineral admixtures and polypropylene fibers represents a watershed moment in the advancement of SCC technology [M.T. Bassuoni et al. (2009)]. Mineral admixtures such as FA, GGBS and SF when used to produce SCC enhanced interaction on the size distribution of particles. The usage of mineral admixtures as cement substitutes in SCC is adopted. The parameter analysed by incorporating mineral admixtures in SCC is rheological properties flowability, mechanical properties [Osama Ahmed Mohamed et al. (2016)].

The self-compacting concrete incorporating FA as a cementitious replacement was investigated for fresh concrete properties. SCC improved the characteristics of workability when produced with the addition of FA. It was noted that the increase in FA content increased the slump flow values [Mehmet Gesoglu et al. (2007); A. M. Falmata et.al. (2019)]. Inclusion of GGBS and SF also improve the reoogical property [O.M. Ofuyatan et al. (2019)], but as compared to FA improving reological property contribution is lesser [Aseel Madallah Mohammeda et.al. (2021)]. Inclusion of these mineral admixture improves mechanical strength. Addition of class F FA attain strength at later ages due to more content of SiO2 but GGBS and SF attain strength at early ages due to presence of more content CaO.[A. M. Falmata et.al. (2019); Osama Ahmed Mohamed et al. (2016)]. Mineral admixtures played a crucial role in enhancing the mechanical properties and long-term durability of concrete [Kazim Turk et al. (2012); Abu Sayed Mohammad Akid et al. (2021)].

Meanwhile, polypropylene fibers offer a synergistic reinforcement mechanism that enhances toughness and crack resistance and improve mechanical properties of the concrete [Saber Fallah et al. (2016)]. The convergence of these additives in SCC formulations represents a holistic approach to optimizing both fresh and hardened properties, fortifying concrete against chemical ingress and environmental degradation [Okan Karahan et al. (2010)].

The project aims to delve into the synergistic effects of mineral admixtures and polypropylene fibers on the strength properties and sulfate resistance of SCC. Through a comprehensive experimental investigation, the objective is to elucidate the interplay between these components and sulfate ions, shedding light on the mechanisms governing durability in challenging environmental conditions. By bridging the gap between theoretical understanding and practical application, this research seeks to catalyze the adoption of sustainable, resilient construction materials, ushering in a new era of innovation in concrete technology.

II. MATERIALS AND MIX COMPOSITIONS

The ordinary Portland cement (OPC) of grade 43, Ramco brand, adhering to IS: 269-2015 standards have been used. Silica fume, class F fly ash and GGBS form the RMC plant were employed as binders, meeting the specifications of, IS 15388.2003, IS:3812:2003 and IS 16714:2018. The specific gravity of OPC is 3.07 and for SF GGBS and fly ash was found to be 2.12, 2.91, and 2.16 respectively.

Locally available crushed granite aggregate of 20mm down size and 12.5mm down size conforming to Indian Standard Specification was used as coarse aggregate for the present work. The physical properties of coarse aggregate are tabulated in Table 1. Locally available M sand are used for all the mixes. The material was tested in accordance with the Indian standard code of practice sieving the aggregates as per IS: 2386 (Part I) – 1963, methods of test for aggregates for concrete specific gravity, density, voids, absorption, and bulking IS: 2386 (Part III) - 1963 and the results were found to satisfy the relevant Indian standard specification. The physical properties of fine aggregates are listed in Table 2. Super plasticizer Glenium SKY 8233, manufactured by BASF Construction Chemicals (India) Pvt. Ltd. is used for producing quaternary blended self-compacting concrete.

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The fibers were incorporated as polypropylene type with a length of 12 mm and a diameter of 0.025-0.04 mm, as shown in Fig. 1. The fibers a specific gravity of 0.91. Fresh potable water was applied in all mixes to prepare the concrete samples.

Table 1: Physical properties of coarse aggregate.

PROPERTIES	RESULTS
Specific gravity	2.62
Fineness modulus	8.79
Bulk density-compacted	1565 kg/m^3

Table 2: Physical properties of fine aggregates.

PROPERTIES	RESULTS
Specific gravity	2.65
Fineness modulus	3.28
Bulk density	1553 kg/m^3
Grading	Zone II

Fig 1: Polypropylene Fiber

The study included eight types of mix proportions, with the first four mixes excluding fibers and the remaining four incorporating 0.2% polypropylene fibers by the weight of the binder content. The water/binder ratio was determined to be 0.32 by weight. The control mixture included only OPC as the binder while the remaining mixtures incorporated Quaternary (OPC + FA + GGBFS + SF) cementitious blends in which a proportion of 50% OPC was replaced with the mineral admixtures. The replacement percentage for both FA and GGBFS were 10, 20, and 30% while those of Silica fume (SF) of 10% by mass of total cementitious materials. The cast specimens underwent mechanical and durability tests, with the durability test involving exposure to a 15% strength of sodium sulfate solution (Na_2SO_4).

III. PREPARATION OF CONCRETE SPECIMENS AND TESTING METHODS

The concrete mixture was prepared in a Pan mixer. Coarse and fine aggregates were mixed thoroughly, and cement and mineral admixtures were added and mixed properly to obtain a uniform color. In the designs containing PP fibers, fibers are added, to the mix and mixed for 2 min. Subsequently, 60% water was added and the remaining water was mixed with superplasticizer and then added to the pan mix. After the mixing process was complete, necessary tests – Slump Flow, T500, J-ring, V-Funnel, L-Box and U-Box – Test were conducted to determine the Flow properties of the fresh QBSCC. The results of these tests, with the EFNARC requirements for SCCs. The moulds were filled with concrete. Since it is a self-compaction concrete, the concrete flows under its own weight, so the moulds are not vibrated. After the concrete is demoulded, it is transferred to a curing tank. Then specimens are cured in water for 7, 28, and 56 days. Compressive, Split tensile, and Flexural strength tests are performed based, on the IS 516, requirements.

After the samples were cured 7, 28 and 56-day, Cubes of size 150× 150 ×150 mm samples underwent compressive and 150mm diameter 300 mm length cylindrical samples underwent tensile strength tests based, respectively, on the IS 516 and IS 5816:1999 requirements the flexural strength was calculated based the IS 516 requirements using, 100 × 100 × 500 mm prism. Similar test were conducted for sulfate attack specimens: the specimen which cured in water for 7 days and 28 days and then they will cured in 15% strength of sodium sulfate solution.

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IV. RESULTS AND DISCUSSION

4.1 Workability

The test results for Mix-1 to Mix-4 and Mix-1 PPF to Mix-4PPF of Quaternary Blended Self-Compacting Concrete (QBSCC), both with and without fibers respectively, reveal significant variations across crucial parameters. These parameters include slump flow, T_{500} time, V funnel time, L box ratio, and U box, as well as J ring slump. By conducting these testes on fresh concrete values are tabulated in Table 3.

The observed differences indicate diverse behavior among the concrete mixes, highlighting the influence of fiber inclusion and mix composition on SCC performance.

The slump flow value acts more as a qualifying factor of SCC than that of parameters derived from other tests, and slump flow values are classified into SF1, SF2, and SF3, respectively [EFNARC 2005]. The result indicates that substituting cement with mineral admixtures in concrete enhances its workability. However, the addition of polypropylene fibres reduces the concrete's rheological properties. Among the tested mixes, Mix-2, which comprises (50% OPC+10% SF+ 30% FA+ 10% GGBS), demonstrated the highest flow ability. This was evidenced by the highest slump flow measurements of 690 mm and 675 mm for mixes with and without fibers, respectively, along with shortest T500 time of 3.1 seconds and 3.48 seconds respectively. The quaternary blended SCC mixes without fibers, specifically Mix-2 PPF are classified as SF1, remaining mixes are classified as SF2 according to the EFNARC 2005 guidelines, all mix are categorized as VS2 for T_{500}.

Table 3 Flow Properties of QBSCC.

Mix	Mix composition	Slump flow in mm	T_{500} time in seconds	J ring slump in mm	V funnel time in seconds	L box ratio	U box (h_2-h_1) in mm
MIX-1	100%OPC	650	4.6	640	11	0.84	18
MIX-2	50%OPC+10%SF+30%FA+ 10%GGBS	690	3.1	675	6.8	0.93	8
MIX-3	50%OPC+10%SF+20%FA +20%GGBS	680	3.8	670	7.6	0.9	12
MIX-4	50%OPC+10%SF+10%FA +30%GGBS	675	4	665	9	0.87	14
MIX-1 PPF	100% OPC+0.2%PPF	590	6.26	530	15.2	0.77	27
MIX-2 PPF	50%OPC+10%SF+30%FA +10%GGBS+0.2%PPF	675	3.48	650	7.89	0.91	11
MIX-3 PPF	50%OPC+10%SF+20%FA +20%GGBS+0.2%PPF	640	4.63	610	9.25	0.87	16
MIX-4 PPF	50%OPC+10%SF+10%FA +30%GGBS+0.2%PPF	620	5.1	590	11.24	0.83	19

Table 3 illustrates the results of the V-funnel test. Except Mix-2, Mix-3, and Mix -2PPF the values obtained for the quaternary blended SCC mix all falling within the VF2 class according to EFNARC 2005 standards. The incorporation of SCMs enhances the segregation resistance of SCC mixes, attributed to the presence of rounded particles in the SCMs, which reduce inter-granular friction during motion, thereby decreasing V-funnel time. Additionally, the introduction of fibers extends the flow time compared to mixes of the same composition but without fibers.

The U-box test, is aimed at assessing the passing ability of SCC. Results reveal that an increase in fly ash content correlates with a decrease in the difference of filling height, signifying an enhancement in passing ability. Mix 2, comprising (50% OPC+10% SF+ 30% FA+ 10% GGBS), demonstrates the minimum difference in filling height, both with and without fiber mix, suggesting the superior passing ability of SCC. This underscores the positive impact of mineral admixture utilization on enhancing the flowability, passing ability, and filling ability of SCC.

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The passing ability of concrete is measured by indicating the blocking ratio. The blocking ratio of all quaternary blended SCC mixes is in the range of 0.84 to 0.93 for without fiber and 0.77 to 0.91 for with fiber mix and it is well below the limitation suggested in EFNARC 2005. Cement replacement with mineral admixture can improve the passing ability of SCC and decrease the blockage of coarse aggregate to some extent.

From fig 2 suggest that the incorporation of mineral admixtures enhances the rheological properties of concrete, offering an improvement over conventional concrete [S.U. Al-Dulaijan et.al. (2002)]. Mix 2 outperforms the rest in terms of rheological properties, regardless of fiber. Notably, as the proportion of GGBS increases from Mix 2 to Mix 4, and inclusion of polypropylene fiber in mixes there is a gradual decline in slump flow, an increase in the flow time, and slight resistance in the passing ability of concrete, suggests a potential trade-off between flow ability [Abu Sayed Mohammad Akid et.al. (2021)]. Mix 2's superior performance can be attributed to its higher content of fly ash.

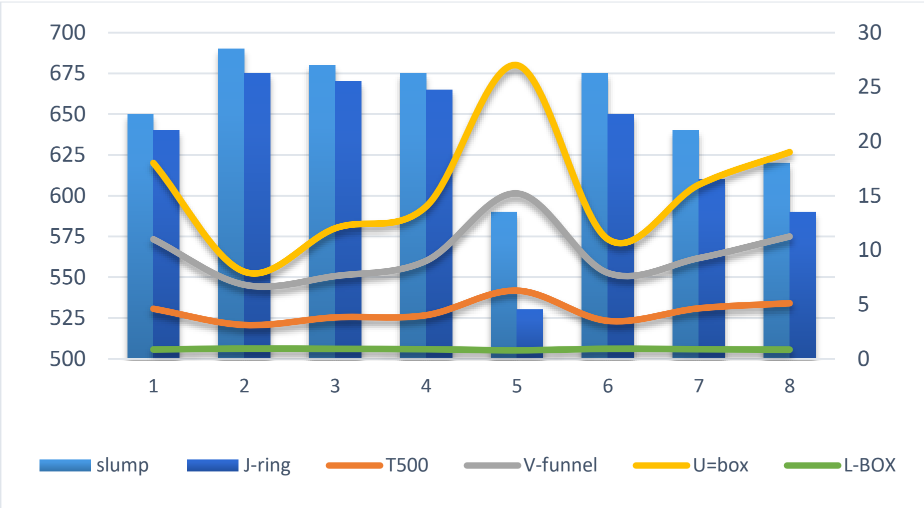

Fig 2: Fresh Property Test

Fly ash, a pozzolanic material with fine particle size, is introduced into a concrete mix alongside cement, its particles act as microscopic spheres or ball bearings. These fine particles, being smaller than typical cement particles, fill the interstitial spaces between the larger cement grains. As a result, they create a lubricating layer that allows the cement particles to move more freely and slide past each other with reduced resistance. The reduction in friction facilitates better workability and flow without compromising the stability of the fresh concrete. Silica fume also contributes in increasing the flow ability of the concrete whereas the addition of Polypropylene fibers makes the mix more viscous thus slowing down the flow of concrete resulting in a decrease in the workability of concrete.

4.2 Strength Properties of Quaternary Blended Self-compacting Concrete

In this study, the fundamental mechanical properties of SCC were investigated with a focus on compressive strength, split tensile strength, and flexural strength.

4.2.1 Compressive strength

Compressive strength assessments for each self-compacting concrete mix were conducted on standard cube specimens (150×150×150 mm) after 7-day 28-day and 56 days of curing periods. The compressive strength values for all the self-compacting concrete mixes obtained are presented in the table 4.

The Compressive strengths of the QBSCC mixes prepared with SCM and 0.2% polypropylene fibers are shown in Table 4 and Figure 3 Graphical representation of the Compressive strength As curing time increases from 7 to 56 days, there is a general trend of performance improvement across all mixes. However, the rate of performance improvement varies for each mix, suggesting differences in the kinetics of hydration and strength gain. Mix-4 and Mix 4 PPF consistently demonstrated the highest performance values across all time intervals compared to the other mixes. This superiority may be due to the higher content of GGBS [S.S. Vivek et al. (2017)] and the incorporation of polypropylene fibers, which increases the compressive strength of the concrete. The cube compressive strength of specimen Mix 2 (50% OPC+10% SF+ 30% FA+ 10% GGBS), on days

7 and 28 was 9.15% and 3.82% lower, respectively, than that of specimen Mix-1. Mix-2 PPF (50% OPC+10% SF+ 30% FA+ 10% GGBS+ 0.2% PPF) is 7.19% and 3.07% lower than that of the Mix 1 PPF on the 7th day, and 28th day, respectively [Mehmet gesoglu et al. (2007);] Indicating that substantially replacing OPC with FA in SCC resulted in considerably lower cube compressive strength due to its slow pozzolanic reaction. Compressive strength is increased by 5.06% and 7.60% compared to mix 1 and mix 1 PPF on 56 days this could attributed to the enhancement in the pozzolanic reaction of FA at the later ages[Kazim Turk et.al. (2012);]. The cube compressive strength of all the specimens (50% SCM) was higher than that of the control specimens with and without fibers, indicating that replacing OPC with a combination of FA, GGBS, and SF resulted in an increase in the compressive strength [A. M. Falmata et.al. (2019); O.M. Ofuyatan et al. (2019); Aseel Madallah Mohammeda et.al. (2021)].When comparing mix 3 and mix 4 with mix 1, there was a rise in compressive strength by 1.97%, 3.93%, and 12.38% for mix 3, and by 2.32%, 6.71%, and 13.37% for mix 4. This increase was observed over the periods of 7 days, 28 days, and 56 days, respectively.

Table 4: Compressive Strength of QBSCC.

MIX	7 Days	28 Days	56 Days
MIX-1	30.17	41.43	44.12
MIX-2	27.41	39.85	46.34
MIX-3	30.77	43.06	49.58
MIX-4	30.87	44.21	50.02
MIX-1 PPF	31.56	44.25	47.34
MIX-2 PPF	29.29	42.89	50.94
MIX-3 PPF	33.30	46.96	55.15
MIX-4 PPF	34.17	49.52	56.64

Similarly, when comparing mix 3PPF and mix 4PPF with mix 1PPF, there was a more significant increase in compressive strength. For mix 3PPF, the increase was 5.51%, 6.12%, and 16.5%, and for mix 4PPF, it was 8.27%, 11.91%, and 19.65%. This increase was also observed over the same periods of 7 days, 28 days, and 56 days, respectively. This is mainly attributed to the pozzolanic reaction and synergy between these SCMs with different particle sizes. It is evident from Fig. 3 that at a given SCM replacement level, replacing the cement by a combination of FA, GGBS and SF has consistently increased the compressive strength, similarly addition of fiber also slight increases the strength when compared to without fiber. For MIX-1PPF resulted in an increase of 4.6%, 6.8%, and 7.3% in strength at 7, 28, and 56 days, respectively. For MIX-2PPF, an increase of 6.8%, 7.6%, and 9.8% were observed at the same intervals. For MIX-3PPF, an increase of 8.2%, 9%, and 11.23% was observed. Finally, MIX-4PPF showed an increase of 10.68%, 12%, and 13.24%, respectively. The addition of PP fibers did not significantly affect the compressive strength in all samples; however, the compressive strength was greater than that of the control sample [Okan Karahan et al. (2010)]. The enhancement in strength is due to the effect of aggregate and fiber interlocking mechanisms, which prevented and delayed the extensive generation of micro cracks and the ability to restrain the extension of cracks, reduce the stress concentration at the tip of cracks, change the direction of cracks, and delay the growth rate of cracks. According to the test results, Comparing the performance of quaternary SCC mixes with Mix 4 PPF (50% OPC+10% SF+10%FA + 30% GGBS + 0.2% PPF) with other mixes it emerges as the top-performing variant across all time intervals. According to the test results, the conclusion can be drawn that using a combination of FA, GGBS, and SF can increase the cube compressive strength of SCC mixes. This is mainly attributed to several reasons: firstly, several previous programs have concluded that GGBS has hydraulic activity with cement in addition to certain pozzolanic activity. Secondly, SF with a high reactivity can react with calcium hydroxide (Ca (OH)2) to form calcium silicate hydrate (C-S-H) which is more denser. Silica fume with a fine particle can fill the surface pores of concrete and pack the pores in a cement matrix and fill the interfacial transition zone, effectively, thus enhancing the compactness of the structure and increasing the compressive strength of SCC mixes. Finally, the remarkable synergistic effect between FA, GGBS, and SF leads to a higher packing density and denser microstructure, thus contributing to an increase in the compressive strength of SCC.

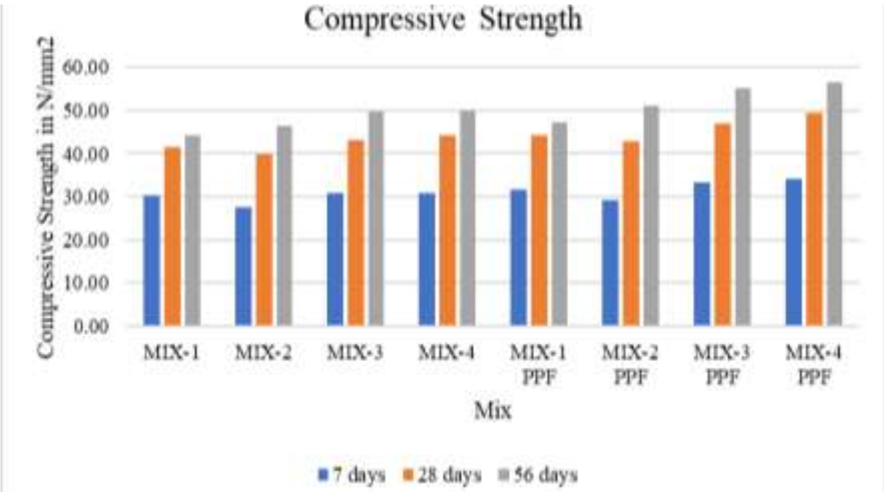

Fig 3: Compressive Strength of QBSCC

4.2.2 Split Tensile Strength

The tensile strength of various concrete mixtures was assessed using cylindrical specimens subjected to testing at 7 days, 28 days, and 56 days of curing. The split tensile strength values for all the self-compacting concrete mixes obtained are presented in the Table 5.

Table 5: Split Tensile Strength of QBSCC.

MIX	7 Days	28 Days	56 Days
MIX-1	2.37	3.08	3.35
MIX-2	2.07	2.95	3.40
MIX-3	2.43	3.12	3.71
MIX-4	2.62	3.35	4.00
MIX-1 PPF	2.55	3.38	3.62
MIX-2 PPF	2.31	3.32	3.90
MIX-3 PPF	2.75	3.67	4.30
MIX-4 PPF	3.02	4.01	4.81

The split tensile strengths of the QBSCC mixes prepared with SCM and 0.2% polypropylene fibers after 7, 28, and 56 days are shown in Table 5 and Figure 4 Graphical representation of the split tensile strength. Similar to the compressive strength, the split tensile strength decreased with increasing FA replacement due to the low reactivity of FA. The percentage decrease in split tensile strength at 7 and 28 days was found to be 12.67% and 4.38%, respectively, for specimens without PPF and 9.41% and 1.78%, respectively, for specimens with PPF. On 56 days of curing, a percentage increase of 1.53% was observed in the absence of PPF and 7.73% in the presence of PPF mix. It was clear that the rate of strength gain increased with an increase in curing age.

A similar behavior was also observed: the early-age compressive strength of FA replaced concrete mix was less than that of the conventional mix, but the rate of strength increased with increasing curing age. The split tensile strength was higher than that of the conventional specimen for Mix-3 and Mix-4. This is due to the high reactivity and high surface area of SCM, which enhance the strength by forming C-S-H gel. The split tensile strength increased at 7 days (2.57%, 10.51%), 28 days (1.17%, 8.76%), and 56 days (10.58%, 19.36%), for Mix-

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3 and Mix-4, respectively. When Mix-1PPF was compared with Mix-3PPF and Mix 4-PPF, the percentage increases in split tensile strength were 7.96% and 18.43% for 7 days, 8.58% and 18.64% for 28 days, and 18.78% and 32.87% for 56 days of curing, respectively. Conversely, QBSCC mixed with SCM and 0.2% polypropylene fibers exhibited split tensile strength values ranging from 2.31 to 3.02 MPa at 7 days, 3.90–4.81 MPa at 28 days, and 3.90–4.81 MPa at 56 days. The split a conventional mix with PPF and without PPF, the split tensile strength values are observed. The increase ranges from 7.59% to 15.3% at 7 days, 9.6% to 19.56% at 28 days, and 8% to 20.23% at 56 days for all SCC mixed with PPF. This enhancement in strength is attributed to the addition of polypropylene fiber [Abu Sayed Mohammad Akid et.al. (2021); Vahid Afroughsabet et al. (2015); Saber Fallah et al. (2016)], which resisted the opening and expansion of early and micro cracks and prevented the continuity of crack formation and propagation due to the fibers' bridging effects in the samples. The enhancement of compressive strength is also reflected in the split tensile strength of the SCC mixes. The addition of SCM has varying effects on the split tensile strength of QBSCC mixes compared to the reference Mix-1 and Mix-1PPF mix. QBSCC Mix-4 and Mix-4PPF show better split tensile strength properties compared to other QBSCC mixes. The addition of SCM to the QBSCC mixture increases the split tensile strength compared with that of conventional mixtures [Saber Fallah et al. (2016); Abu Sayed Mohammad Akid et.al. (2021);]. SCM improves packing and fills voids, resulting in denser concrete. In addition, the late pozzolanic reaction of SCM contributes to an increase in the split tensile strength at later ages.

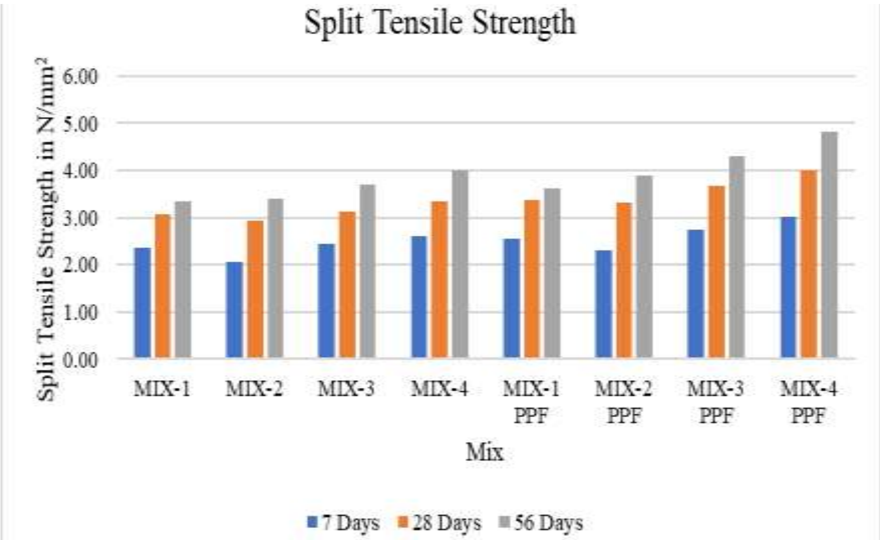

Fig 4: Split Tensile Strength of QBSCC

4.2.3 Flexural strength

The flexural strength values for all the self-compacting concrete mixes obtained are presented in the Table 6. The flexural strength results for the SCC mix at 7, 28 and 56 days are presented in Table 6 and. Figure 5 shows the graphical representation of Flexural strength. QBSCC mixes prepared with SCM exhibit flexural strength values ranging from 4.19 MPa to 4.86 MPa at 7 days 6.02 MPa to 6.15 MPa at 28 days and 6.19 MPa–6.73 MPa at 56 days. Conversely, mixes prepared with SCM and 0.2% PPF demonstrate flexural strength values ranging from 4.47 MPa to 5.53 MPa at 7 days , 6.60 MPa to 7.20 MPa at 28 days and 6.73 MPa–7.90 MPa at 56 days. The flexural strength was higher than that of the conventional specimen (Mix-1) for the replacement of Mix-3 and Mix-4. The flexural strength increased at 7 days (12.77%, 16%), and 56 days (4.85%, 8.87%) for Mix-3 and Mix-4, respectively.

When Mix-1PPF was compared with Mix-3PPF and Mix -4 PPF, the percentage increases in flexural strength were 18.66%, 23.88% for 7 days, 6.06%, 9.09% for 28 days, and 6.93% and 17.33% for 56 days of curing, respectively. The flexural strength values for MIX-1 increased by 6.59%, 9.63%, and 8.78% at 7, 28, and 56 days, respectively, on comparing without PPF mix with the PPF incorporated mix. For MIX-2, an increase of 10.26%, 11.38%, and 12.56% were observed at the same intervals .For MIX-3 containing PPF, an increase of 12.15%, 14.75%, and 10.94% was observed. Finally, MIX-4PPF showed an increase of 13.83%, 17.16%, and 17.31%, respectively.

Table 6: Flexural Strength of QBSCC.

MIX	7 Days	28 Days	56 Days
MIX-1	4.19	6.02	6.19
MIX-2	3.93	5.75	6.21
MIX-3	4.73	6.10	6.49
MIX-4	4.86	6.15	6.73
MIX-1 PPF	4.47	6.60	6.73
MIX-2 PPF	4.33	6.40	6.99
MIX-3 PPF	5.30	7.00	7.20
MIX-4 PPF	5.53	7.20	7.90

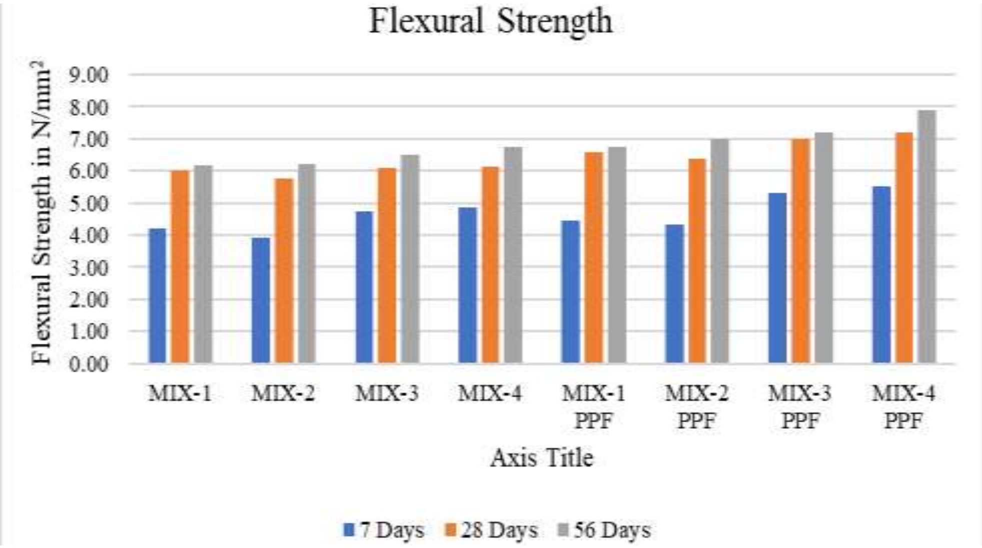

Fig 5: Flexural Strength of QBSCC

The increase in flexural strength is due to the addition of SCM has diverse effects on the flexural strength of QBSCC mixes compared to the reference mix, incorporation of fiber also facilitated in achieving the flexural strength due to the bridging effect of fiber as a result of a satisfactory mechanical bond among the fibers and concrete [Vahid Afroughsabet et al. (2015)]. In other words, when a flexural load is applied to the fiber-reinforced concrete, the fiber present in the concrete is acted as a secondary reinforcement to bridge the crack by providing resistance to the crack propagation at the failure plane. Mix-4PPF exhibits the highest flexural strength, while Mix-1 shows the lowest. The flexural strength is often higher than split tensile strength in concrete is due to the nature of the stresses involved. In a flexural strength test, the highest stress occurs at the outermost fibers of the beam, which are furthest from the neutral axis, while the material within the neutral axis experiences lower levels of stress. This allows the material to carry a higher load and thus exhibit a higher flexural strength.

4.3 Durability: Sulfate Attack

The test was conducted on SCC specimens of cubes, cylinders, and prisms. Sodium sulfate with a strength of 15% was used to evaluate the sulfate resistance of the mixes. The specimens were initially water-cured for 7 and 28 days. Four mixes without fiber and with polypropylene fiber SCC specimens, after immersing in a 15% Na2SO4 solution for 28 days of exposure to sulfate attack. This type of attack represents an accelerated testing procedure, indicating the performance of concrete mixes against sulfate attack. In ASTM C1012, provisions are made for researchers to adjust the concentration of the solution to suit the exposure environment.

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From fig 6, for mixes without fiber addition, mixes 1 to 4 show varying percentages of weight gain across different curing durations (7 days and 28 days water cured) and specimen types (cubes, cylinders, and prisms). Notably for 7 days water cured under sulfate attack, mixes 1 generally exhibit higher weight gain values compared to Mixes 3 and 4, suggesting that increasing proportions of supplementary cementitious materials like fly ash, silica fume and GGBFS while reducing cement content, can potentially improve resistance to sulfate attack and reduce gain in weight [S.U. Al-Dulaijan et.al. (2002); M. T. Bassuoni et al. (2008)]. For mixes without fiber addition, the Mix-4 shows greater reduction in weight gain as compared to all mixes. Conversely, for mixes with fiber addition, similar trends are observed, with Mixes 1ppf and 2ppf showing higher weight gain values compared to Mixes 3ppf and 4ppf. For mixes with fiber addition, the mix-4ppf shows greater reduction in weight gain as compared to all mixes. The test conducted data indicates a noticeable decrease in weight gain after 28 days of curing in water and immersion in a sodium sulfate solution for both mixes (without fiber and with fiber addition). Compared to both mixes (with and without fiber addition) the mix-4ppf shows greater reduction in weight gain as compared to all mixes.

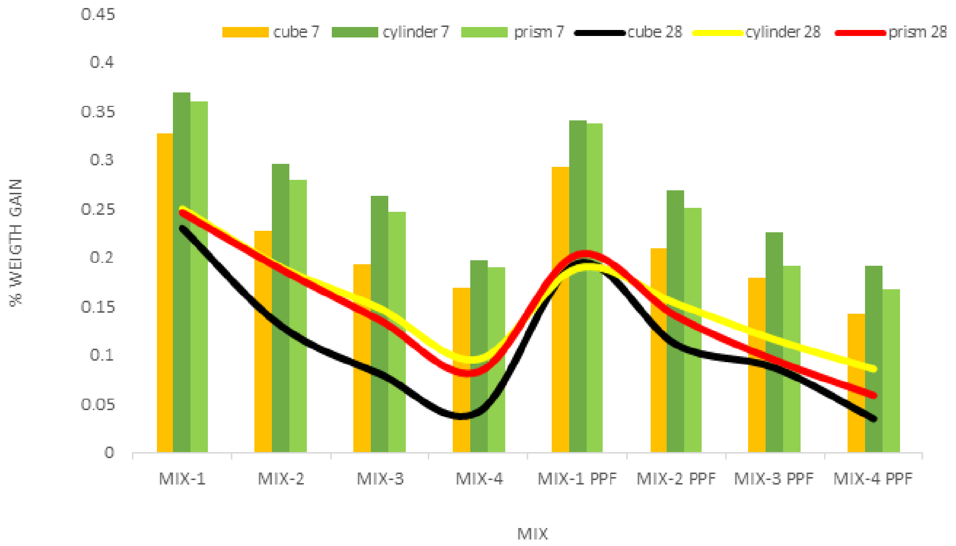

Fig 6: Percentage weight gain in Na2SO4 solution cured

In concrete mixes with a high cement content or insufficient curing time, there may be unhydrated cement particles remaining within the concrete matrix. When immersed in a sodium sulfate solution, these unhydrated particles can continue to hydrate, leading to an increase in weight. The increase in weight due to immersion in sodium sulfate can be attributed to the reaction of sodium sulfate with certain compounds present in the concrete, such as calcium hydroxide (Ca(OH)2) and calcium aluminate hydrates (C-A-H phases), forming secondary compounds like gypsum (calcium sulfate) and ettringite. Supplementary cementitious materials is finely ground, allowing it to fill the voids between cement particles effectively, thereby reducing overall porosity and making the concrete less susceptible to sulfate penetration and subsequent expansion. GGBFS plays a significant role in reducing weight gain in concrete subjected to sodium sulfate attack. Moreover, GGBFS contains reactive calcium aluminates and calcium sulfates, which react with sulfate ions in the sodium sulfate solution to form stable compounds that inhibit sulfate ingress and reduce the expansion of sulfate-bearing compounds within the pores, thus limiting weight gain. Furthermore, the hydration products formed from GGBFS, such as calcium silicate hydrate (C-S-H) gel and calcium aluminate hydrates, contribute to denser and more impermeable microstructures, further reducing pathways for sulfate ingress and minimizing the expansion of sulfate-bearing phases, consequently lowering weight gain. Finally, the incorporation of fibers into the concrete matrix not only enhances its microstructure by effectively mitigating crack formation but also contributes to a reduction in porosity. This decrease in porosity restricts the movement of sulfate solution within the concrete pores, consequently leading to a noticeable reduction in weight gain.

The research examines how immersion in a sodium sulfate solution affects the strength of various SCC mixes, both with and without the addition of fibers are shown in Table 7. The variations in compressive, split tensile, and flexural strengths observed among the different SCC mixes, both with and without fiber addition, can be attributed to several factors, including the composition of the mixes and the presence of PPF.

From fig 7, 8, and 9, mixes containing supplementary cementitious materials generally exhibited lower percentage losses in strength after exposure to sodium sulfate solution [S.U. Al-Dulaijan et.al. (2002); H.N. Atahan et al. (2011); Dezhi Wang et.al. (2017)]. Mixes with higher concentration of GGBS shows more resistance to sulfate attack, with addition of fiber increases its performance against sodium sulfate attack [Muzeyyen Balcikanli Bankir et al. (2020)]. From fig 7, the loss in compressive strength for MIX-4 and MIX-4PPF subjected to 7 days water cured 28 days of sodium sulfate attack were compared with the strength attained in 28days water cured specimen it was observed to be 4.74% and 2.8% respectively, similarly for 28 days water cured strength and 28 days sodium sulfate attack were compared with the strength attained in 56 days water cured specimen it was observed loss of 1.20% and -0.29% respectively. Similarly, from fig 8, the loss in split tensile strength for MIX-4 and MIX-4PPF 5.49% and 3.43% respectively for 7 days water cured, similarly for 28 days water cured 2.99% and 1.23% respectively. Similarly, from fig 9 the loss in flexural strength for MIX-4 and MIX-4PPF 5.42% and 3.12% respectively for 7 days water cured, similarly for 28 days water cured 2.23% and 1.01% respectively. The loss in strength due to sulfate attack is more in 7 days as compared to 28 days water cured, and also in split tensile specimen as compared to all other specimen.

Table 7: Loss of Strength after 28 Days Immersion in a Sodium Sulfate Solution for Different SCC Mixes

Type of mix	Compressive strength after 28 days immersion in Na_2SO_4 media		split tensile strength after 28 days immersion in Na_2SO_4 media		flexural strength after 28 days immersion in Na_2SO_4 media	
	7 days water cured	28 days water cured	7 days water cured	28 days water cured	7 days water cured	28 days water cured
MIX-1	37.78	42.02	2.79	3.16	5.46	5.85
MIX-2	36.80	44.95	2.71	3.24	5.29	5.95
MIX-3	40.78	48.63	2.89	3.57	5.68	6.26
MIX-4	42.12	49.42	3.17	3.88	5.81	6.58
MIX-1 PPF	41.15	45.95	3.08	3.46	6.05	6.46
MIX-2 PPF	40.45	50.10	3.08	3.77	5.96	6.80
MIX-3 PPF	45.37	54.52	3.49	4.20	6.66	7.08
MIX-4 PPF	48.13	56.80	3.87	4.76	6.98	7.82

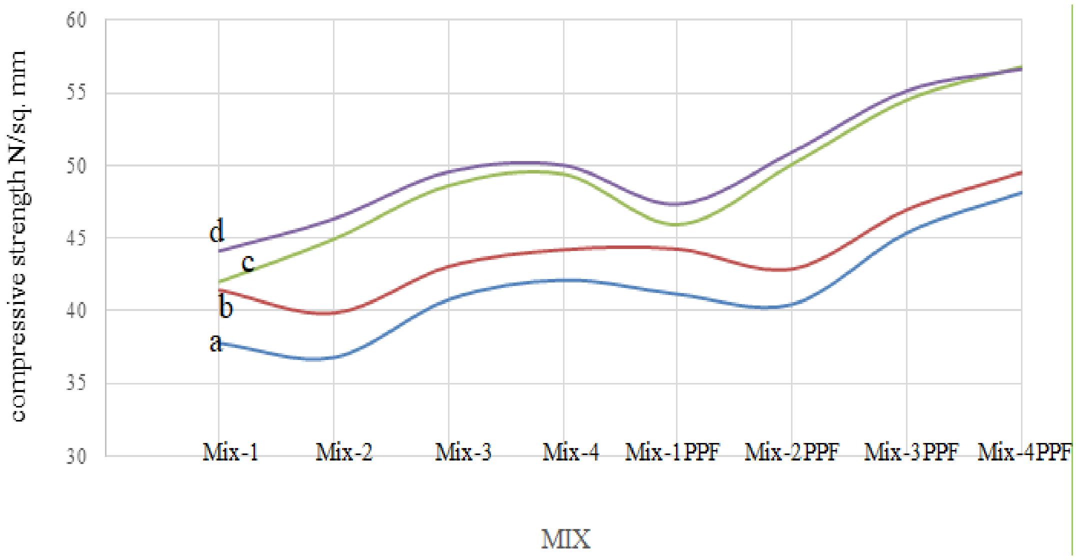

Fig 7: Cube strength after curd in Na_2SO_4 solution

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Fig 8: Cylinder strength after curd in Na_2SO_4 solution

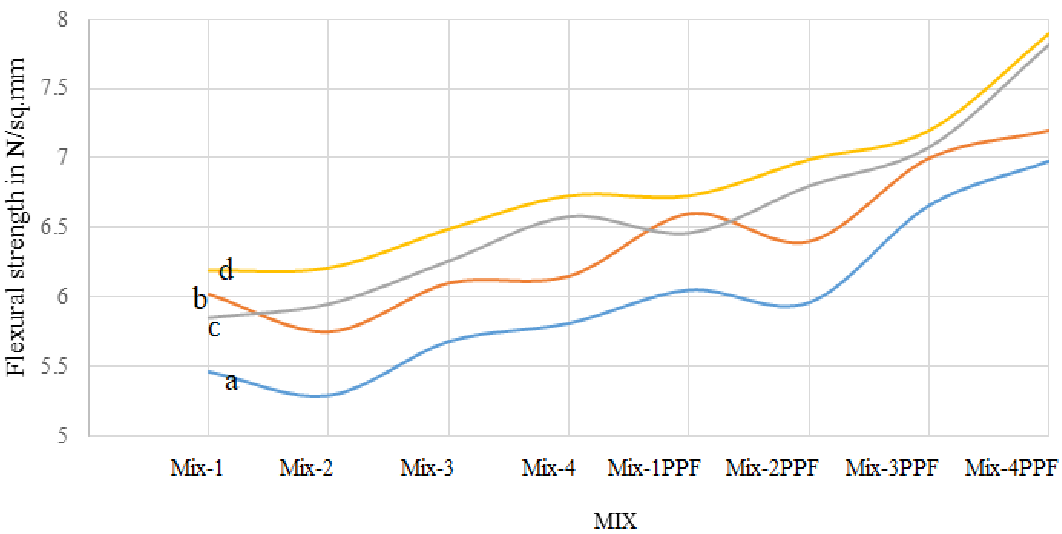

Fig 9: Prism strength after curd in Na_2SO_4 solution

a) 7 days water cured and 28 days Na_2SO_4 solution cured, b) 28 days water cured, c) 28 days water cured and 28 days Na_2SO_4 solution cured, d) 56 days water cured

The mineral admixture plays important role against sulfate attack. GGBFS, fly ash, and silica fume is finely ground, allowing it to fill the voids between cement particles more effectively. The hydration products formed from SCM's, such as calcium silicate hydrate (C-S-H) gel and calcium aluminate hydrates, contribute to denser and more impermeable microstructures. This pore refinement leads to a reduction in the overall porosity of the concrete. As a result, the pathways for sulfate ingress are minimized, and the expansion of sulfate-bearing phases is restricted. GGBFS contains reactive calcium aluminates and calcium sulfates. When sodium sulfate penetrates the concrete, it reacts with these compounds to form stable sulfate-bearing phases. These stable compounds can inhibit further ingress of sulfates into the concrete and reduce the expansion of sulfate-bearing phases within the pores. Hence, the increase in GGBFS content in all mixes improve the resistance against sodium sulfate attack. Mix 4, both with and without fiber addition, exhibits superior resistance compared to all other mixes, attributed to its 30% GGBFS content. Silica fume is often considered one of the most effective SCMs due to its rapid pozzolanic reaction and ability to produce dense and impermeable hydration products. These products create a barrier against sulfate ingress and help mitigate expansion and deterioration caused by sulfate attack. Finally, the incorporation of fibers into the concrete matrix not only enhances its microstructure by effectively mitigating crack formation but also contributes to a reduction in porosity. This decrease in porosity restricts the movement of sulfate solution within the concrete pores, consequently leading to a noticeable change in strength when compared to the without fiber addition concrete. Hence MIX-1 to MIX-4 with addition of fiber shows better results against sodium sulfate attack. MIX-4PPF dominates over all mixes.

V. CONCLUSION

Mix design based on Okumara and Ozawa can be successfully employed for achieving SCC. SCC can be successfully produced by replacing cement with various mineral admixtures such as fly ash, GGBS and silica fume with a proper proportioned mix. Synergetic effects of mineral admixtures give better results.

- The study reveals significant variations in slump flow, T500 time, V funnel time, L box ratio, and U box among QBSCC mixes, underscoring the influence of both mix composition and fiber inclusion on the fresh properties of the concrete.
- Substituting cement with mineral admixtures such as fly ash, GGBS and silica fume enhances the workability of QBSCC, while the addition of polypropylene fibers tends to reduce rheological properties.
- Mix-2, characterized by a composition comprising 50% OPC, 10% SF, 30% FA, and 10% GGBS, notably distinguishes itself with superior rheological properties. This underscores the critical significance of meticulously fine-tuning mix designs to attain the targeted fresh properties.
- Generally, increases with curing time, Mixes with higher GGBS content and fiber inclusion exhibit higher compressive strengths. Compared to control mix, there was decrease in strength or only marginal increase in strength properties of blended mixes at 7- and 28-days water curing. This may be due to slow pozzolanic reaction due to cement replacement of fly ash, but inclusion of silica fume influences the strength at early ages.
- It was observed that 56 days strength of blended mixes was higher when compared to control mix. The enhancement of strength may be due to increased pozzolanic reaction and synergetic effect of various admixtures used.
- The addition of fiber mainly impacts on increasing the tensile strength of concrete, hence split tensile and flexural strength was more when compared to the mixes without fiber. The enhancement in strength is due to the bridging effect of the fibers in the samples.
- Among the blended concrete mixes, Mix-4PPF, OPC replacement with 30% GGBS, 10% FA, 10% SF showed higher strength when compared to combinations whereas it was lesser for the control mix.
- The percentage gain in weight was more for 7 days water cured specimens than the 28 days water cured specimens subjected to 28 days sulphate attack.
- Mix-4 emerges as the most resilient mix against sodium sulfate attack, attributed to its optimized composition, including higher GGBFS content. The inclusion of fibers further enhances its resistance, with Mix-4PPF exhibiting superior performance against sulfate attack.
- The incorporation of supplementary cementitious materials SCM's such as fly ash, GGBFS, and silica fume significantly enhances the resistance of concrete to sodium sulfate attack. Higher proportions of SCMs lead to denser microstructures, reducing porosity and limiting sulfate ingress.
- GGBFS demonstrates particular effectiveness in improving sulfate resistance due to its reactive compounds, which form stable phases inhibiting further sulfate ingress and expansion within concrete pores.
- The addition of polypropylene fibers enhances concrete microstructure by mitigating crack formation and reducing porosity, thereby improving resistance to sulfate attack.

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