

Performance Evaluation of High-Volume Fly Ash Concrete Reinforced with Steel Fibers for Rigid Pavement Applications

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Abstract – High-volume fly ash concrete (HVFAC) is a sustainable cement-reduced material with potential for rigid pavement construction, but the replacement of a large fraction of cement by fly ash can reduce early-age strength and can increase sensitivity to workability and environmental exposure. The present investigation evaluates fiber-reinforced high-volume fly ash concrete (FRHVFAC) containing Class F fly ash and crimped steel fibers at 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6 and 1.8% by volume. An M40 mixture with 50% cement replacement by fly ash was proportioned using the CANMET absolute-volume approach at a water-to-binder ratio of 0.30. Compressive, split tensile, flexural and impact strengths were determined after 7, 28 and 90 days of normal water curing. Separate durability programmes subjected companion specimens to 90 days of sulphuric-acid exposure at pH 2.5 and potassium-sulphate exposure at 15% concentration. Across the normal, acidic and sulphate

environments, the principal strength measures generally increased with fiber addition up to 1.4% and then declined. Under normal curing, 1.4% fiber produced 60.00 MPa compressive strength, 3.94 MPa split tensile strength and 7.44 MPa flexural strength at 90 days, corresponding to increases of about 17%, 19% and 29% over the control. Under acidic attack, the corresponding 90-day values were 45.33, 2.94 and 5.59 MPa; under sulphate attack they were 49.19, 3.28 and 6.20 MPa. The results indicate that a controlled steel-fiber dosage improves the load-carrying and crack-resisting characteristics of HVFAC and can support rigid pavement applications where aggressive exposure is anticipated.

Keywords: high-volume fly ash concrete; steel fiber; FRHVFAC; rigid pavement; compressive strength; split tensile strength; flexural strength; impact strength; acidic attack; sulphate attack.

1. INTRODUCTION

Rigid pavements are widely used where high load-carrying capacity, long service life and resistance to repeated wheel loading are required. Conventional cement concrete, however, has a relatively high cement demand and consequently a high embodied-energy and carbon burden. High-volume fly ash concrete provides an alternative by replacing a substantial fraction of Portland cement with a pozzolanic industrial by-product. The uploaded project investigates this concept specifically for pavement-quality concrete and further introduces crimped steel fibers to improve tensile, flexural and impact response.

The project is based on an M40 concrete in which 50% of the cement is replaced by Class F fly ash. Because high-volume fly ash systems can develop strength more slowly at early ages, the investigation evaluates 7-, 28- and 90-day performance. Steel fibers are introduced over a broad range from 0 to 1.8% by volume so that both the beneficial and adverse effects of increasing fiber concentration can be identified.

The experimental programme also considers aggressive environments relevant to pavement service: sulphuric-acid exposure at pH 2.5 and potassium-sulphate exposure at 15% concentration, each maintained for 90 days after water curing.

The combination of strength testing and environmental exposure allows the fiber dosage to be assessed not only for conventional mechanical performance but also for retention of strength under chemically aggressive conditions.

1.1 Problem Statement

Large-scale use of Portland cement in pavement concrete is associated with high material consumption and environmental impact, while high-volume fly ash mixtures may show lower early-age strength. Pavements are also exposed to cracking, repeated impact, tensile stresses and, in some locations, acidic or sulphate-bearing environments. A material that combines high fly ash utilization with fiber-based crack control therefore requires systematic evaluation across different ages and exposure conditions.

1.2 Aim and Objectives

- To evaluate the mechanical performance of fiber-reinforced high-volume fly ash concrete intended for rigid pavement applications.
- To study the influence of 0–1.8% crimped steel fiber on compressive, split tensile, flexural and impact strengths at 7, 28 and 90 days.
- To determine the fiber dosage giving the most favorable overall strength response.

- To investigate strength retention after 90 days of sulphuric-acid exposure at pH 2.5.
- To investigate strength retention after 90 days of potassium-sulphate exposure at 15% concentration.
- To interpret the observed optimum in terms of fiber dispersion, void filling, crack bridging and workability.

1.3 Significance of the Study

The work is significant because it combines high-volume fly ash utilization with discrete steel-fiber reinforcement in an M40 pavement concrete. The project results indicate that a moderate fiber dosage can substantially increase tensile, flexural and impact capacity while maintaining the long-term compressive performance of the fly-ash-rich binder system. The study therefore provides a laboratory basis for considering FRHVFAC in rigid pavement applications, particularly where crack resistance and impact tolerance are important.

2. LITERATURE REVIEW

Mallik (2005): Discussed the use of fly ash in structural concrete and described high-volume fly ash concrete and roller-compacted concrete applications. The work emphasized lower heat of hydration and potential advantages for pavement and dam construction.

Prabir C. Basu and Subhajit Sarswati (2006): Reported trials on high-volume fly ash concrete using Indian ingredients and observed slower early-age strength development with substantial later-age strength gain.

Crouch, Mewitt and Byard (2007): Compared high-volume fly ash mixtures with conventional transportation concrete and reported comparable or higher ultimate compressive strength together with lower absorption and water-permeable void content.

Shunzhii Qian and Li V. C. (2008): Investigated engineered cementitious composite for durable pavement and linked high tensile ductility and fatigue resistance with improved pavement service-life potential.

Siddique (2008): Studied high-volume Class-F fly ash concrete reinforced with natural fibers and found improvements in fracture toughness and impact resistance as fiber content increased.

Indrajit Patel and Modhera (2010): Examined fiber-reinforced high-volume fly ash concrete and reported satisfactory workability and later-age strength, with fiber addition contributing to improved performance.

Bentz and Ferraris (2010): Discussed rheology and setting of high-volume fly ash mixtures and the potential for delayed setting, emphasizing the need for admixture and mixture control.

Fatah M. Wegian et al. (2011): Investigated steel-fiber and fly-ash combinations and observed that steel fibers were particularly effective in improving flexural tensile behavior.

Sarvan Raja Mohan and Parthiban (2011): Studied fly-ash-based steel-fiber concrete and reported improved strength

and energy absorption with suitable combinations of fly ash and fiber.

Bentz et al. (2011): Evaluated thermal properties of high-volume fly ash mortars and concretes and highlighted the influence of material composition on thermal conductivity and heat capacity.

Binod Kumar et al. (2007): Reported that high-volume fly ash mixtures with 50–60% fly ash can be proportioned for pavement applications and noted long-term strength development and reduced drying shrinkage at suitable water-to-cementitious ratios.

2.1 Research Gap

The literature reviewed in the project demonstrates that high-volume fly ash concrete can achieve suitable later-age strength and durability, while steel fibers can improve tensile, flexural and impact performance. However, the combined response of 50% fly ash concrete over a broad steel-fiber range under both normal curing and chemically aggressive acid and sulphate exposures is less clearly established. The present study addresses this gap by using the same M40 mixture and fiber series across all environments, enabling direct comparison of strength trends and optimum dosage.

3. MATERIALS AND METHODOLOGY

3.1 Materials

Ordinary Portland cement of 43 grade conforming to IS 8112 was used, with a reported specific gravity of 3.15. Class F fly ash obtained from RTPS, Raichur, was used as the mineral replacement; its reported specific gravity was 2.5 and fineness was 469 kg/m². River sand obtained near Harihar from the Tungabhadra river bank was used as fine aggregate and was reported as Zone II, with specific gravity 2.66 and fineness modulus 2.65. Locally available granite coarse aggregate of 20 mm and 12 mm nominal sizes was blended; its specific gravity was 2.72, combined fineness modulus 6.53 and water absorption 0.94%.

Conplast SP430 sulphonated naphthalene formaldehyde condensate was used as the superplasticizer. The project reports a dosage of 1.1% by weight of binder content in the experimental procedure. Crimped steel fibers manufactured by Stewols India (P) Ltd. were used. The reported fiber length was 38 mm, average equivalent diameter 0.75 mm, aspect ratio 50 and maximum tensile strength 828 MPa. Potable tap water was used for mixing and curing.

Table 1. Principal materials used in the investigation

Material	Reported property	Value
Cement	Grade / specific gravity	OPC 43 / 3.15
Fly ash	Class / specific gravity	Class F / 2.50
Fly ash	Fineness	469 kg/m ²
Fine aggregate	Zone / specific gravity	Zone II / 2.66
Fine aggregate	Fineness modulus	2.65
Coarse aggregate	Specific gravity	2.72

Coarse aggregate	Water absorption	0.94%
Steel fiber	Length / diameter	38 mm / 0.75 mm
Steel fiber	Aspect ratio	50
Steel fiber	Maximum tensile strength	828 MPa

3.2 Mix Design and Mixture Proportions

The M40 mixture was designed using the CANMET guidelines and the absolute-volume method. The target strength was reported as 49.24 MPa, and a water-to-binder ratio of 0.30 was selected. Cement replacement by fly ash was fixed at 50%. The initial mixture proportion was reported as 1:1.17:2.54 for binder:fine aggregate:coarse aggregate. Trial batches were used to check fresh properties and strength before finalizing the mixture.

Table 2. Reported final HVFAC mix proportions

Parameter	Final reported value
Concrete grade	M40
Cement	254.78 kg/m ³
Fly ash	254.78 kg/m ³
Water	152.81 kg/m ³
Coarse aggregate	1294.25 kg/m ³
Fine aggregate	596.17 kg/m ³
Water/binder ratio	0.30
Plasticizer	0.55% (14.96 litre) as reported in final mix table
Mix proportion	1 : 1.17 : 2.54

The project contains a dosage inconsistency for the superplasticizer: the experimental-procedure text reports 1.1% by weight of binder, whereas the final mix-proportion table reports 0.55% (14.96 litre). The present paper retains both statements as source-reported values and does not silently reconcile them.

3.3 Fiber Dosage and Experimental Programme

Ten fiber contents were investigated: 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6 and 1.8% by volume. For normal curing, specimens were tested after 7, 28 and 90 days. For chemical exposure, specimens were first water cured for the specified age and then immersed for 90 days in the relevant aggressive solution before strength testing.

Table 3. Experimental exposure programme

Environment	Exposure condition	Ages evaluated	Fiber range
Normal water curing	Water curing	7, 28, 90 days	0–1.8%
Acidic attack	H ₂ SO ₄ , pH 2.5, 90 days	7, 28, 90 days before exposure	0–1.8%
Sulphate attack	K ₂ SO ₄ , 15%, 90 days	7, 28, 90 days before exposure	0–1.8%

3.4 Test Methods

Compressive strength was measured using 150 mm cubes in accordance with the project procedure based on IS 516. Split tensile strength was obtained from 150 mm diameter × 300 mm cylinders using the relationship $f^t = 2P/(\pi DL)$. Flexural strength was determined using 100 × 100 × 500 mm beams under two-point loading, with the modulus of rupture calculated from the maximum load. Impact performance was evaluated using repeated blows from a 4.54 kg hammer dropped from 460 mm, with impact energy calculated as whn .

For acidic attack, specimens were exposed to sulphuric acid maintained at pH 2.5 for 90 days. For sulphate attack, potassium sulphate solution at 15% concentration was used for 90 days. Specimens were weighed before and after exposure and then tested for the relevant mechanical property. The project also describes thermal conductivity and coefficient of linear expansion testing; however, the uploaded PDF ends before the thermal-property results are available, so no thermal numerical results are reproduced in this paper.

4. RESULTS AND DISCUSSION

4.1 Normal Water Curing

The normal-curing results show a clear age-dependent increase in strength and a consistent influence of fiber content. For all three mechanical strength measures, the response rises up to 1.4% steel fiber and then decreases slightly at 1.6–1.8%. This behavior indicates that fiber bridging and crack restraint dominate at moderate dosages, while excessive fiber content can reduce workability and make uniform mixing and compaction more difficult.

Table 4. Compressive Strength (MPa) under normal curing

Fiber vol. (%)	7 days	28 days	90 days
0.0	19.56	43.33	51.11
0.2	20.00	44.74	52.74
0.4	20.78	46.07	54.37
0.6	21.33	47.41	56.00
0.8	22.26	49.19	58.22
1.0	22.74	50.37	59.41
1.2	22.89	50.37	59.70
1.4	22.96	50.96	60.00
1.6	22.67	50.37	59.41
1.8	22.59	50.22	59.26

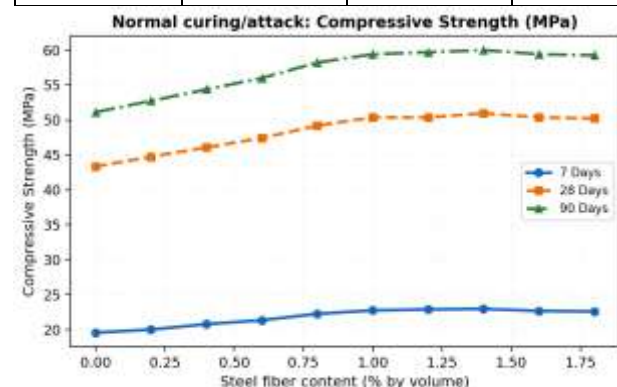


Figure 1. Variation of compressive strength (mpa) with steel-fiber content under normal water curing.

Table 5. Split Tensile Strength (MPa) under normal curing

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		1.74	2.35	3.30
0.2		1.86	2.65	3.30
0.4		1.91	2.74	3.37
0.6		2.02	2.83	3.54
0.8		2.09	3.02	3.57
1.0		2.22	3.17	3.62
1.2		2.32	3.27	3.84
1.4		2.41	3.30	3.94
1.6		2.38	3.28	3.87
1.8		2.31	3.21	3.82

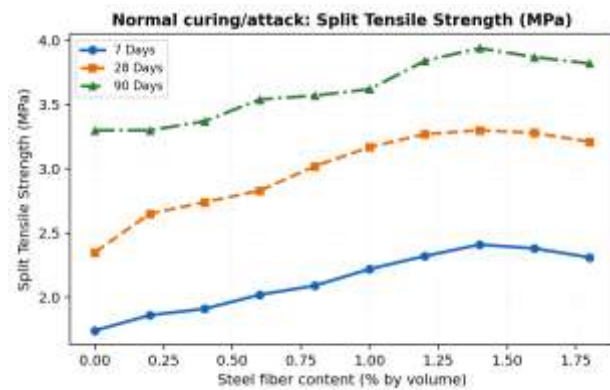


Figure 2. Variation of split tensile strength (mpa) with steel-fiber content under normal water curing.

Table 6. Flexural Strength (MPa) under normal curing

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		2.21	3.37	5.77
0.2		2.77	4.20	6.29
0.4		3.07	4.63	6.64
0.6		3.15	4.96	7.05
0.8		3.43	5.18	7.11
1.0		3.81	5.77	7.13
1.2		3.84	5.87	7.32
1.4		3.97	5.99	7.44
1.6		3.93	5.94	7.40
1.8		3.87	5.91	7.37

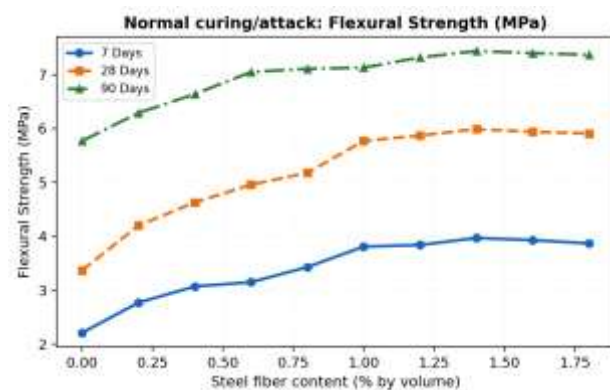


Figure 3. Variation of flexural strength (mpa) with steel-fiber content under normal water curing.

Table 7. Impact Energy (N-m) under normal curing

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		1348.61	2060.95	2458.71
0.2		2178.52	3326.56	3968.59
0.4		2558.90	3893.67	4645.15
0.6		3084.51	4682.09	5585.73
0.8		3561.71	5415.18	6460.30
1.0		3575.54	5435.92	6485.06
1.2		3969.75	6030.69	7194.62
1.4		4156.48	6293.50	7508.14
1.6		3872.92	5885.46	7021.35
1.8		3298.90	5014.05	5981.76

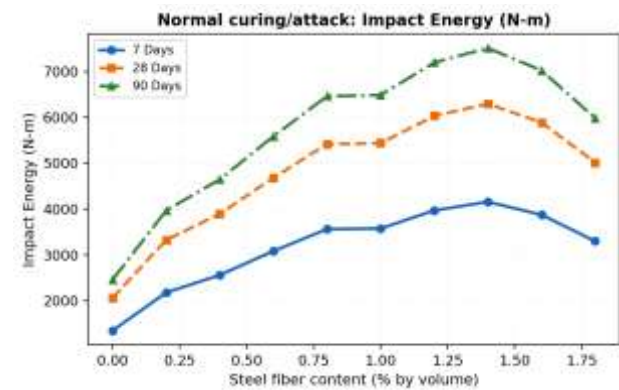


Figure 4. Variation of impact energy (n-m) with steel-fiber content under normal water curing.

At 1.4% fiber, the 90-day compressive strength reaches 60.00 MPa compared with 51.11 MPa for the control, an increase of about 17.4%. The corresponding split tensile and flexural strengths are 3.94 and 7.44 MPa, representing increases of approximately 19.4% and 28.9%. The largest relative benefit is observed in flexural behavior, which is particularly relevant to rigid pavement slabs.

Impact energy also increases markedly with fiber content. At 90 days, the control records 2458.71 N-m, whereas 1.4% fiber reaches 7508.14 N-m, approximately 205% higher than the reference. The decline at 1.6–1.8% indicates that the optimum is not obtained by simply maximizing fiber content.

4.2 Performance under Acidic Attack

After 90 days of sulphuric-acid exposure at pH 2.5, the same general fiber-response pattern remains evident. Strength increases progressively up to 1.4% fiber and then decreases. The results indicate that the fiber network, together with the dense fly-ash-rich matrix, helps maintain mechanical integrity under acidic exposure.

Table 8. Compressive Strength (MPa) after acidic attack

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		14.67	32.44	38.30
0.2		14.96	33.48	39.63
0.4		15.59	34.52	40.89
0.6		16.00	35.56	42.07
0.8		16.67	36.89	43.70
1.0		17.00	37.70	44.44

1.2	17.15	37.93	45.19
1.4	17.19	38.15	45.33
1.6	17.07	37.70	44.59
1.8	16.93	37.63	44.30

1.2	2.92	4.41	5.49
1.4	2.95	4.45	5.59
1.6	2.89	4.41	5.48
1.8	2.84	4.37	5.39

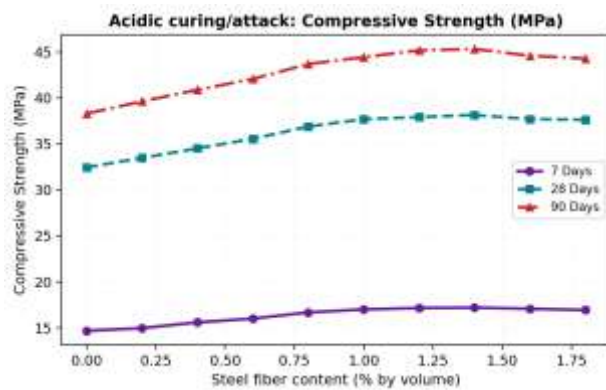


Figure 5. Variation of compressive strength (mpa) after sulphuric-acid exposure.

Table 9. Split Tensile Strength (MPa) after acidic attack

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		1.30	1.73	2.48
0.2		1.39	1.98	2.52
0.4		1.44	2.05	2.53
0.6		1.51	2.12	2.65
0.8		1.57	2.26	2.68
1.0		1.66	2.37	2.71
1.2		1.70	2.44	2.89
1.4		1.82	2.53	2.94
1.6		1.78	2.50	2.90
1.8		1.74	2.46	2.82

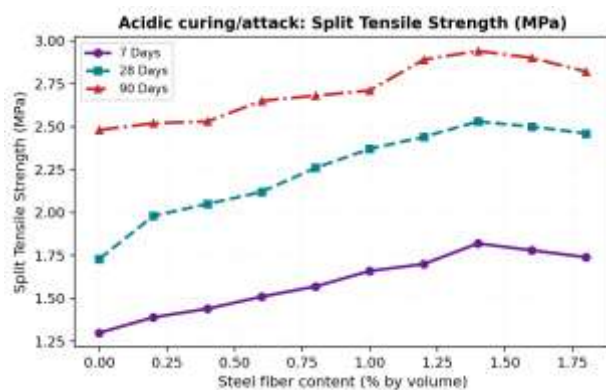


Figure 6. Variation of split tensile strength (mpa) after sulphuric-acid exposure.

Table 10. Flexural Strength (MPa) after acidic attack

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		1.65	2.53	4.33
0.2		2.08	3.15	4.73
0.4		2.29	3.47	4.99
0.6		2.36	3.71	5.29
0.8		2.57	3.88	5.33
1.0		2.85	4.33	5.36

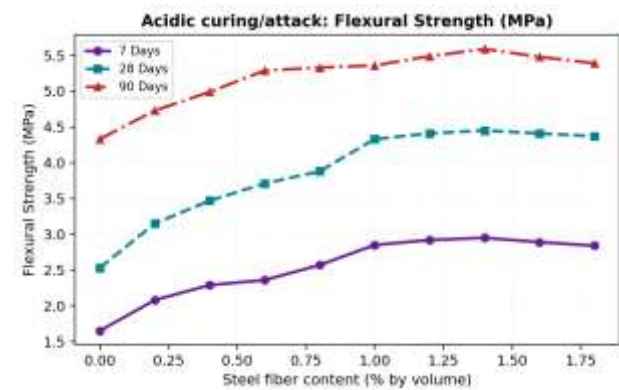


Figure 7. Variation of flexural strength (mpa) after sulphuric-acid exposure.

Table 11. Impact Energy (N-m) after acidic attack

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		1009.73	1549.17	1818.89
0.2		1639.08	2496.65	2925.44
0.4		1915.71	2918.52	3416.47
0.6		2316.84	3520.21	4114.98
0.8		2676.47	4066.57	4758.16
1.0		2683.38	4080.40	4771.99
1.2		2980.77	4529.94	5304.52
1.4		3126.00	4723.58	5532.75
1.6		2911.61	4412.37	5166.20
1.8		2475.90	3762.27	4398.53

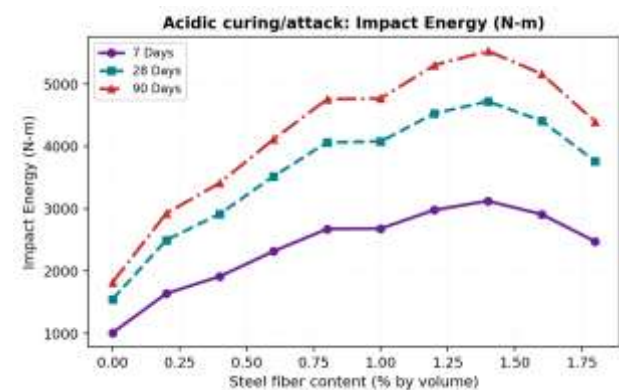


Figure 8. Variation of impact energy (n-m) after sulphuric-acid exposure.

At 1.4% fiber, 90-day post-exposure compressive strength is 45.33 MPa versus 38.30 MPa for the control, an increase of approximately 18.4%. Split tensile strength rises from 2.48 to 2.94 MPa and flexural strength from 4.33 to 5.59 MPa, corresponding to increases of about 18.5% and 29.1%, respectively. The project interprets these gains as evidence that steel fibers reduce crack development and help form a denser, more continuous composite response under aggressive exposure.

The 90-day impact energy at 1.4% fiber is 5532.75 N-m compared with 1818.89 N-m for the control, an increase of approximately 204%. Thus, the impact response is substantially more sensitive to fiber reinforcement than compressive strength.

4.3 Performance under Sulphate Attack

Sulphate-exposed specimens were immersed in 15% potassium sulphate solution for 90 days after water curing. The compressive, split tensile and flexural results again show a maximum around 1.4% fiber. This consistency across normal and chemical environments is an important outcome because it suggests that the optimum fiber dosage is governed principally by composite mechanics and workability rather than by the exposure environment alone.

Table 12. Compressive Strength (MPa) after sulphate attack

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		16.22	36.00	42.44
0.2		16.59	37.04	43.85
0.4		17.22	38.21	45.04
0.6		17.74	39.33	46.52
0.8		18.44	40.89	48.30
1.0		18.81	41.70	48.74
1.2		19.00	41.85	49.04
1.4		19.04	42.15	49.19
1.6		18.89	41.78	48.89
1.8		18.74	41.70	48.89

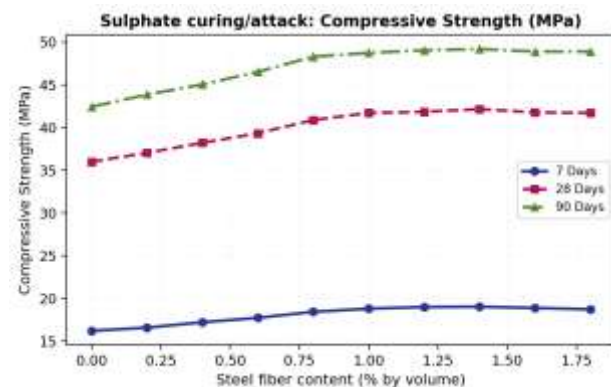


Figure 9. Variation of compressive strength (mpa) after sulphate exposure.

Table 13. Split Tensile Strength (MPa) after sulphate attack

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		1.41	1.92	2.75
0.2		1.53	2.16	2.76
0.4		1.59	2.23	2.81
0.6		1.67	2.26	2.94
0.8		1.73	2.36	2.97
1.0		1.84	2.45	3.01
1.2		1.87	2.51	3.22
1.4		1.99	2.55	3.28
1.6		1.96	2.49	3.25
1.8		1.94	2.45	3.17

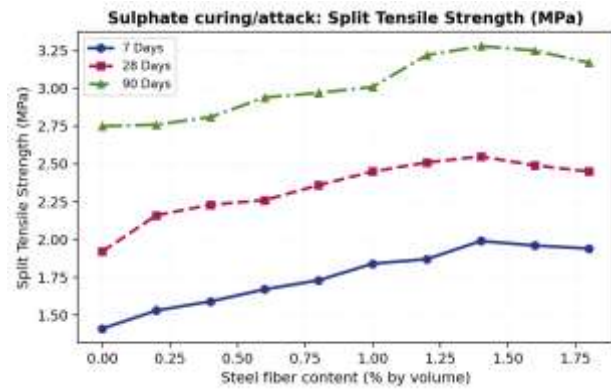


Figure 10. Variation of split tensile strength (mpa) after sulphate exposure.

Table 14. Flexural Strength (MPa) after sulphate attack

Fiber vol.)	(%)	7 days	28 days	90 days
0.0		1.84	2.79	4.79
0.2		2.29	3.48	5.23
0.4		2.53	3.85	5.51
0.6		2.61	4.09	5.85
0.8		2.84	4.29	5.91
1.0		3.17	4.79	5.92
1.2		3.23	4.88	6.08
1.4		3.32	4.91	6.20
1.6		3.27	4.87	6.16
1.8		3.23	4.84	6.12

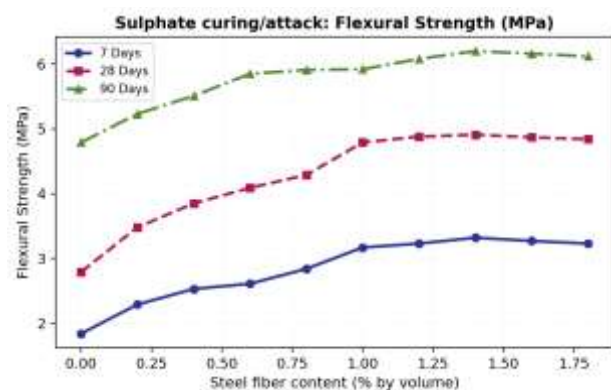


Figure 11. Variation of flexural strength (mpa) after sulphate exposure.

At 1.4% fiber, the 90-day compressive strength is 49.19 MPa compared with 42.44 MPa for the control, an increase of approximately 15.9%. Split tensile strength rises from 2.75 to 3.28 MPa and flexural strength from 4.79 to 6.20 MPa, corresponding to increases of approximately 19.3% and 29.4%. These results support the beneficial role of steel fibers in retaining tensile and flexural capacity under sulphate exposure.

The uploaded PDF includes the detailed 7-day sulphate-impact table but ends before the consolidated 28- and 90-day sulphate-impact results and the later parts of the thermal-property chapter. Consequently, those unavailable numerical results are not fabricated or inferred in this paper.

4.4 Cross-Environment Comparison

Table 15. Ninety-day performance at the optimum 1.4% fiber dosage

Exposure	90-d compressive (MPa)	90-d split tensile (MPa)	90-d flexural (MPa)
Normal	60.00	3.94	7.44
Acidic	45.33	2.94	5.59
Sulphate	49.19	3.28	6.20

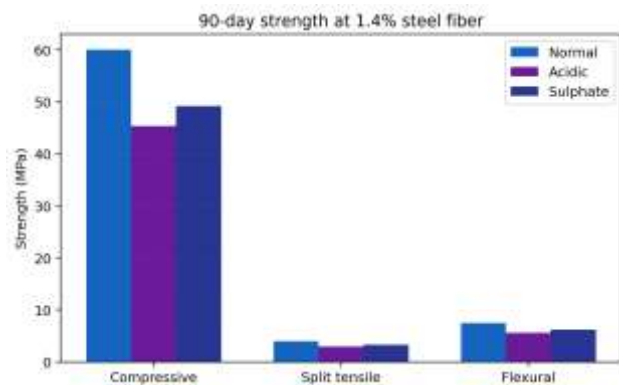


Figure 12. Cross-environment comparison of 90-day strength at 1.4% steel fiber.

The cross-environment comparison confirms that normal water curing gives the highest absolute strengths, followed by sulphate and acidic exposure. Nevertheless, the fiber-reinforced mixtures preserve a substantial fraction of their strength in both aggressive media. The common optimum at 1.4% is especially useful for practical pavement material selection because it provides a single dosage that performs favorably under all three investigated exposure conditions.

4.5 Mechanism of Improvement

Steel fibers act primarily through crack bridging, stress redistribution and energy absorption. At low and moderate fiber contents, fibers intercept developing cracks and transfer tensile stress across crack faces, increasing split tensile and flexural strength. The improvement in impact energy is especially large because repeated impact requires energy dissipation through fiber pull-out, debonding and crack deflection. The fly ash contributes to later-age matrix refinement through pozzolanic reaction, while the fiber network provides a complementary mechanism for controlling macro-crack propagation.

Beyond approximately 1.4% fiber, the project observes a reduction in strength. This is consistent with the practical difficulty of dispersing larger fiber quantities uniformly in a low-workability mixture. Fiber clustering, increased internal resistance during mixing and reduced compaction can introduce defects that offset the additional bridging capacity. The optimum is therefore interpreted as a balance between reinforcement efficiency and workability.

4.6 Engineering Implications

- The 1.4% steel-fiber dosage provides the highest reported 7-, 28- and 90-day compressive, split tensile and flexural strengths within the tested range.

- Flexural strength benefits are more pronounced than compressive strength benefits, making the mixture particularly relevant to rigid pavement slabs where flexural stress governs slab response.
- Impact energy increases substantially with steel-fiber addition, indicating improved resistance to repeated localized loading and fracture propagation.
- The optimum remains near 1.4% under acidic and sulphate exposure, suggesting that the reinforcement effect is robust across the investigated environments.
- The study supports the use of high-volume fly ash as a cement-reduction strategy, while the steel fibers compensate for part of the tensile and flexural limitations of high-volume fly ash concrete.
- Field implementation should still verify workability, fiber dispersion, pavement fatigue, abrasion, moisture transport, freeze-thaw behavior where relevant, and long-term field performance.

4.7 Limitations and Future Research

The numerical dataset in the uploaded project is based on mean results from three specimens for each condition, but replicate-level statistical measures such as standard deviation and confidence intervals are not consistently reported. The final PDF also does not contain the later consolidated sulphate-impact results or the thermal-property results listed in the project index. Future work should therefore include complete replicate-level statistical analysis, fatigue testing of pavement beams, abrasion and wheel-loading simulations, permeability and chloride transport measurements, microstructural characterization, and complete thermal testing. A narrow optimization programme around 1.2–1.6% fiber would also help establish the statistical robustness of the observed 1.4% optimum.

5. CONCLUSIONS

- The investigated FRHVFAC consisted of M40 concrete with 50% cement replacement by Class F fly ash and crimped steel fibers ranging from 0 to 1.8% by volume.
- Under normal water curing, compressive, split tensile and flexural strengths increased with fiber content up to 1.4% and then decreased slightly.
- At 90 days and 1.4% fiber, compressive strength reached 60.00 MPa, split tensile strength 3.94 MPa and flexural strength 7.44 MPa, representing increases of approximately 17%, 19% and 29% over the control.
- The 90-day impact energy increased from 2458.71 N-m for the control to 7508.14 N-m at 1.4% fiber, an improvement of about 205%.
- After sulphuric-acid exposure at pH 2.5, the 1.4% mixture achieved 45.33 MPa compressive, 2.94 MPa split tensile and 5.59 MPa flexural strength at the reported 90-day condition.
- After 15% potassium-sulphate exposure, the 1.4% mixture achieved 49.19 MPa compressive, 3.28 MPa split tensile and 6.20 MPa flexural strength at 90 days.
- The consistent optimum near 1.4% fiber across normal, acidic and sulphate environments indicates that controlled

steel-fiber reinforcement can improve the mechanical resilience of high-volume fly ash concrete.

8. The results support FRHVFAC as a promising rigid-pavement material, while field-scale adoption requires further durability, fatigue, abrasion, workability and long-term valid

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