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Investigation on the Performance of High-Volume Fly Ash Concrete Reinforced with Fibers for Rigid Pavement

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Abstract - Fly ash has significant potential in high-volume fly ash concrete (HVFAC) due to its favorable physico-chemical properties. Extensive research in India and abroad has examined its strength and performance characteristics. In India, most ready-mixed concrete plants in the private sector commonly use 20–30% fly ash as part of the cementitious material, whereas several government agencies remain cautious. At construction sites with batching plants, typical fly ash replacement levels are around 25–30%. In contrast, site-mixed concrete using tilting drum mixers rarely uses fly ash directly, though blended cements containing 22–32% fly ash are widely used; in fact, nearly 60–70% of cement produced in India is blended. HVFAC generally replaces more than 50% of cement with fly ash and requires very low water content. To maintain workability, high-range water reducers or superplasticizers are used. Although HVFAC exhibits lower early compressive strength than conventional concrete, it develops excellent long-term strength along with improved elastic modulus, flexural, tensile, and abrasion performance. Research at CANMET-MTL in Canada initiated the development of HVFAC in 1985, with an emphasis on low cement content, a low water-to-binder ratio, and fly ash contents of up to 55%. HVFAC offers reduced CO_2 emissions, lower environmental impact, and improved durability, making it suitable for mass and structural concrete applications.

Key Words: High-Volume Fly Ash Concrete (HVFAC), Blended Cement, Fly Ash Utilization, Sustainable Construction, Cement Replacement, and Mechanical and Durability Properties.

1. INTRODUCTION

Fly ash is a major by-product generated from coal combustion, especially in coal-based thermal power plants used for electricity production. Although other by-products, such as bottom ash and gypsum, are also produced, their quantities are significantly smaller compared to fly ash. Worldwide, the effective utilization of fly ash remains a challenge, and a significant portion is still disposed of in ash ponds or used in low-value applications such as landfilling, soil improvement, road base layers, land reclamation, or as a raw material in cement manufacturing. Among all possible uses, the most valuable and high-volume application of fly ash is concrete, where it serves as a beneficial partial replacement for cement, offering both environmental and economic advantages. In India, where approximately 65–70% of electricity is generated from coal, fly ash production is around 110 million tonnes per year and is expected to increase with rising energy demand. Much of this ash is still handled in its wet form and disposed of in ash ponds, which raises environmental concerns and underutilizes a valuable resource. However, fly ash possesses excellent physico-chemical properties that make it suitable for High-Volume Fly Ash Concrete (HVFAC). While ready-mixed concrete plants commonly use 20–30% fly ash, HVFAC typically incorporates more than 40% fly ash, which requires a low water content and often necessitates the use of superplasticizers. HVFAC generally exhibits lower early strength but significantly improved long-term mechanical performance.

Although concrete is naturally strong in compression and weak in tension, the addition of steel fibres has been shown to improve tensile strength, ductility, and crack resistance. When fibres are combined with high volumes of fly ash, the resulting Fiber-Reinforced HVFAC exhibits enhanced compressive and tensile performance, making it a superior composite for structural applications. Furthermore, HVFAC makes a significant contribution to sustainability by reducing cement consumption, lowering CO_2 emissions, minimizing landfill waste, and enhancing energy efficiency in construction. The long-term durability, reduced permeability, improved resistance to chemical attack, and enhanced microstructure of HVFAC make it an ideal choice for modern infrastructure, where longevity and environmental responsibility are paramount. As research advances, the combined use of fibres and high fly ash volumes promises to further expand the applications of this innovative material.

1.1 Objectives

The primary objective of this proposed research work is to develop fiber-reinforced high-volume fly ash concrete (FRHVFAC) as a material for constructing rigid pavements. To achieve the above objective, the following experimental works are planned.

• To find out the strength properties of fiber-reinforced high-volume fly ash concrete, such as compressive strength, tensile strength, flexural strength, and impact strength required for rigid pavements.

• To find out the resistance of fiber-reinforced high-volume fly ash concrete to acidic attack.

• To find out the resistance of fiber-reinforced high-volume fly ash concrete to chloride attack.

• To study the behaviour of fiber-reinforced high-volume fly ash concrete under temperature variations.

2. LITERATURE REVIEW

Fwa, T. F., and Paramasivam, P. (1990) investigated the use of thin steel fiber cement mortar overlays for rehabilitating deteriorated concrete pavements. Their study focused on improving abrasion resistance and restoring or enhancing load-carrying capacity. Experimental results showed that adding steel fibers significantly improved abrasion resistance, with 0.5% and 1% fiber content reducing abrasion loss by 13% and 18%, respectively. Unlike plain mortar, steel fiber mortars maintain abrasion resistance under wetting–drying cycles. The overlays also demonstrated superior load capacity, especially when properly bonded to the base pavement. A 40 mm overlay with 1% steel fibers provided the best flexural performance and durability.

Ramakrishnan V., Balaguru P., Kostaneski L., and Johnston D. (1990) evaluated the field performance of fiber-reinforced concrete (FRC) highway pavements using hooked-end steel fibers at a dosage of 39.2 kg/m³. The concrete was designed for a compressive strength of 40 MPa, and trial mixes were tested for compressive, flexural, fatigue, and impact strengths up to 28 days. Additional specimens and core samples were taken during construction for comparison. Their study examined the differences between laboratory and field mixes, the performance of control versus fiber-reinforced samples, and the overall pavement condition. Results showed that FRC can be placed with standard equipment and provides superior fatigue resistance and crack control compared to plain concrete.

Tarun R. Naik, Shiw S. Singh, and Mohammad M. Hossain (1994) evaluated the effect of high volumes of Class C fly ash on the permeability of concrete. A reference air-entrained mix without fly ash was designed to achieve a strength of 41 MPa, and additional mixes incorporated 0–70% fly ash as a cement replacement. Each mixture was tested for compressive strength, chloride permeability (ASTM C1202), and air and water permeability using the Figg method. For up to 28 days, plain concrete exhibited air permeability lower than high-volume fly ash mixes. By 91 days, the 50% fly ash mix exhibited the lowest air and water permeability. Fly ash generally reduces chloride permeability by up to 50% when used in a 50% replacement ratio.

Siddique and Karanbir Singh (1999) investigated the effect of sand fibers on the impact strength of high-fly ash concrete. Cement was partially replaced with 40%, 45%, and 50% fly ash, and san fibers of 25 mm length were added at 0.25–1.00% by volume. Impact strength tests were conducted on 500 × 500 × 30 mm sheets after 28 and 90 days using the drop-weight method. Results showed a significant increase in ultimate impact strength with fiber addition, reaching up to 3 times improvement at 28 days and 4.5 times at 90 days for a 40% fly ash and 1% fiber mixture. Fiber dosage did not affect first-crack initiation; however, a higher fiber content changed the failure behavior from brittle to ductile, characterized by multiple cracks.

Jiang L. H. and Malhotra V. M. (2000) investigated how large volumes of ASTM Class F and Class C fly ash affect the water demand of non-air-entrained concrete. Eight different fly ashes from Canada and the USA were studied, each used as a 55% cement replacement without the addition of superplasticizer. Results showed a substantial reduction in water demand, ranging from 8.8% for fly ash from Lingan, Nova Scotia, to 19.4% for fly ash from Coal Creek, USA. The resulting mixes had slumps ranging from 57 to 70 mm. To achieve slumps above 100 mm while maintaining strength, the authors noted that water reducers or superplasticizers would be required.

Shunzhi Qian and Li V. C. (2008) examined the use of Engineered Cementitious Composite (ECC), a highly ductile concrete, as an alternative pavement material. Their study combined flexural fatigue testing with FEM analysis to evaluate pavement performance. Results showed that ECC's high tensile ductility allows fatigue-induced fractures to disperse into microcracks, preventing major cracking. ECC demonstrated excellent fatigue resistance, significantly enhancing pavement durability and service life. The authors concluded that ECC can effectively replace conventional concrete in rigid pavements. Moreover, due to its superior fatigue performance, pavement thickness could be reduced by more than 50% while maintaining equivalent service life.

Indrajit Patel and Modhera C. D. (2010), in their study titled "Study of Basic Properties of Fiber Reinforced High Volume Fly Ash Concrete," investigated the behavior of fiber-reinforced high-volume fly ash concrete (FRHVFAC) containing 50–60% fly ash as a replacement for cement. Their results confirmed that all the developed mix designs satisfy the CANMET guidelines for low, medium, and high-strength HVFA concrete. The mixes were reported to be homogeneous and workable.

The water-to-cementitious material ratio used in the study ranged from 0.25 to 0.40, and the slump after 60 minutes of retention varied between 85 and 100 mm for different mixes. They observed that the early-age strength (3 and 7 days) was relatively lower, especially for mixes containing 60% fly ash and for higher-grade concretes such as M35 and M40. However, after 7 days, the strength gain increased significantly, in the range of 65–76%, and all mixes achieved satisfactory compressive strength by 28 days.

The inclusion of fibers did not alter the water–binder ratio or the 60-minute slump values. Importantly, the authors reported an improvement of 9.75% to 15% in the 28-day compressive strength of FRHVFAC compared to plain concrete.

3. MATERIALS AND METHODOLOGY

3.1 Materials Used

3.1.1 Cement

In the present research work, ordinary Portland cement of 43-grade, as supplied by UltraTech Cement, is used. The tests on cement are conducted in accordance with the Indian Standards,

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conforming to IS: 8112-1989. The physical properties of cement are presented in Table 1.

Table -1. Physical properties of cement

S .No	Property	Result
1	Specific gravity	2.66
2	Fineness modulus	2.65
3	Water absorption	0.91%

Particulars	Result	Permissible Limits
Fineness of cement (%)	5	Should not be more than 10
Normal consistency (%)	30	-
Initial setting time (minutes)	110	Should not be less than 30
Final setting time (minutes)	335	Should not be more than 600
Soundness (mm)	1.5	Shall not have an expansion of more than 10
Compressive strength of mortar cubes (N/mm2) i. 3 days ii. 7 days iii. 28 days	23.66 36.33 45.16	Should not be less than 23 N/mm^2 Should not be less than 33 N/mm^2 Should not be less than 43 N/mm^2

3.1.2 Fly ash

The fly ash used in the present study is taken from Raichur Thermal Station, Shakthinagar, Raichur, Karnataka.

Table - 2. Properties of fly ash

Test conducted	Results
Specific gravity	2.5
Fineness—Specific surface in m^2/kg by Blaine's Air- Air-permeability method, (Minimum)	469
Lime reactivity —Average compressive strength in N/mm2, (Minimum).	4.6
Comparative compressive strength at 28 days, percent (Minimum)	90
Soundness by autoclave test, Expansion of specimens in percentage, (Maximum)	0.0025
Residue on 45-micron sieve, percent (Maximum)	28.5

3.1.3 Fine aggregate

The fine aggregates used in this experimental program were procured locally from the Tungabhadra riverbed near Harihar. The test on sand is conducted according to IS:2386 — 1963 and IS:383-1970. Properties of the fine aggregate used in the experimental work are tabulated in Table 3.

Table -3. Properties of fine aggregate

3.1.4 Coarse aggregate

Locally available crushed granite coarse aggregates, with a maximum size of 20 mm, are used in the present work. The aggregates are tested in accordance with the Indian Standard Specifications IS: 2386-1963. The results of various tests conducted on coarse aggregate are presented in Table 4.

Table - 4. Properties of coarse aggregate

Property	Result
Fineness modulus	6.53
Specific gravity	2.72
Water absorption percentage	0.94%
Crushing value, percentage	26.33%
Impact value, percentage	25.16%
Abrasion value, percentage	24.42%
Flakiness index, percentage	13.60%
Elongation index, percentage	10.36%

3.1.5 Superplasticizer

Conplast- SP430, a concrete superplasticizer based on Sulphonated Naphthalene Polymer is used as a water-reducing admixture and to improve the workability of fly ash concrete. Conplast SP430 has been specially formulated to give high water reductions up to 25% without loss of workability or to produce high quality concrete of reduced permeability. Conplast SP430 is non-toxic. CONPLAST SP430 is marketed by 74 Ws Fosroc Chemicals, Bangaluru.

3.1.6 Steel fibers

Crimped steel fibers manufactured by Mls Stewols India (P) Ltd., Nagapur, are used in the present study. The technical details as provided by product catlog are presented in table 5.

Table -5. Properties of steel fiber

Properties	Results
Maximum tensile strength	828 MPa
Average fiber length	38 mm
Average equivalent diameter	0.75
Average aspect ratio	50
Deformation	Continuously deformed circular segment
Appearance	Bright and clean white.

3.1.6 Water

Water is an essential ingredient in concrete, as it actively participates in the chemical reaction with cement. Since it helps form the strength-giving cement gel, the quantity and quality of water must be carefully considered. Potable water is generally considered satisfactory. In the present investigation, tap water is used for both mixing and curing purposes.

4. EXPERIMENTAL PROCEDURE

M40 concrete mix is designed in accordance with the guidelines of the CANMET handbook, featuring a 50% replacement of cement with fly ash. The mix proportion arrived is 1:1.17:2.54 (BC: FA: CA) with a water-to-binder ratio of 0.3 and a superplasticizer dosage of 1.1% by weight of the binder content (cement + fly ash). Fibers are added at varying percentages of 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 % by volume fraction.

The specimens are cast for testing their compressive strength, split tensile strength, flexural strength, and impact strength. To study strength characteristics under normal conditions, the specimens were cured in water for 7, 28, and 90 days and tested for their respective strengths. The test results are tabulated and shown in graphs for analysis.

5. RESULTS AND DISCUSSIONS

Table 6 gives the overall results of the compressive strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in compressive strength compared to the reference mix. It is observed that the compressive strength of FRHVFAC increases as the percentage of steel fibers in it increases up to 1.4%. Thereafter, the compressive strength shows a decreasing trend. Thus, the higher value of compressive strength may be obtained by using 1.4% steel fibers. This is true for compressive strengths at 7, 28, and 90 days. At a 1.4% addition of steel fibers, the percentage increases in compressive strength after 7 days, 28 days, and 90 days are found to be 17%, 18%, and 17%, respectively. It is also observed that a small percentage of fibers has improved the compressive strength of high-volume fly ash concrete.

Table 7 gives the overall results of the split tensile strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in split tensile strength compared to the reference mix. It is observed that the tensile strength of FRHVFAC increases as the percentage of steel fibers in it increases up to 1.4%. Thereafter, the tensile strength shows a decreasing trend. Thus, the higher value of tensile strength may be obtained by using 1.4% steel fibers. This is true for tensile strengths at 7, 28, and 90 days. At a 1.4% addition of steel fibers, the percentage increases in tensile strength after 7 days, 28 days, and 90 days are found to be 38%, 41%, and 19%, respectively. Additionally, it has been observed that a small percentage addition of fibers has improved the tensile strength of high-volume fly ash concrete.

Table 8 gives the overall results of the flexural strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in split tensile strength compared to the reference mix. It is observed that the flexural strength of FRHVFAC increases as the percentage of steel fibers in it increases up to 1.4%. Thereafter, the flexural strength shows a decreasing trend. Thus, the higher value of flexural strength may be obtained by using 1.4% steel fibers. This is true for 7, 28, and 90 days of flexural strength. At a 1.4% addition of steel fibers, the percentage increases in flexural strength after 7 days, 28 days, and 90 days are found to be 80%, 78%, and 29%, respectively. Additionally, it has been observed that a small percentage addition of fibers has improved the flexural strength of high-volume fly ash concrete.

Table 9 gives the overall results of the impact strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in split tensile strength compared to the reference mix. It is observed that the impact strength of FRHVFAC increases as the percentage of steel fibers in it increases up to 1.4%. Thereafter, the impact strength shows a decreasing trend. Thus, a higher value of impact strength may be obtained by using 1.4% steel fibers. This is true for 7-day, 28-day, and 90-day impact strengths. At a 1.4% addition of steel fibers, the percentage increases in impact strength after 7 days, 28 days, and 90 days are found to be 208%, 205%, and 205%, respectively. Additionally, it has been observed that a small percentage of fibers has substantially improved the impact strength of high-volume fly ash concrete.

The improvement in the strength properties of HVFAC may be attributed to the fact that the addition of fibers enhances the stiffness of concrete. Also, the addition of 1.4% fibers will fill all the major voids, resulting in a dense mass. The addition of more than 1.4% steel fiber results in a decrease in the strength characteristics, as it significantly affects the workability of concrete. Mixing and compaction operations become difficult when more than 1.4% steel fibers are added to high-volume fly ash concrete. Substantial improvements are found in tensile strength, flexural strength, and impact strength when 1.4% steel fibers are added to high-volume fly ash concrete, and a marginal increase is found for compressive strength.

Thus, there is a clear indication that the use of steel fibers in high-volume fly ash concrete can modify the properties to suit it for rigid pavement construction.

Table 10 gives the overall results of the acid compressive strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in compressive strength compared to the reference mix. It is observed that the compression strength of FRHVFAC increases as the percentage of steel fibers in it increases up to 1.4% when subjected to acidic attack. After adding 1.4% steel fibers, the compression strength decreases. Thus, the higher value of compressive strength may be obtained by using 1.4% steel fibers when subjected to acidic attack. This observation is true for 7 days, 28 days, and 90 days of compressive strength. The percentage increase in compressive strength over 7, 28, and 90 days at a 1.4% addition of steel fibers is found to be 17%, 18%, and 18%, respectively. This indicates that a small percentage of steel fibers can resist the acidic attack, thereby improving the compression strength of HVFAC.

Table 11 presents the overall results of the acid-split tensile strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in split tensile strength compared to the reference mix. It is observed that the tensile strength of FRHVFAC when subjected to acidic attack increases as the percentage of steel fibers in it increases up to 1.4%. After 1.4%additions of steel fibers, the tensile strength decreases. Thus, the higher value of tensile strength may be obtained by using 1.4% steel fibers when subjected to acidic attack. This observation is true for 7 days, 28 days, and 90 days of tensile strength. The percentage increases in tensile strength after 7, 28, and 90 days at a 1.4% addition of steel fibers are found to be 40%, 46%, and 19%, respectively. This indicates that a small percentage addition of steel fibers can resist the acidic attack, thereby improving the tensile strength of HVFAC.

Table 12 gives the overall results of the acid flexural strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in split tensile strength compared to the reference mix. It is observed that the flexural strength of FRHVFAC when subjected to acidic attack increases as the percentage of steel fibers in it increases up to 1.4%. After adding 1.4% steel fibers, the flexural strength decreases. Thus, the higher value of flexural strength may be obtained by using 1.4% steel fibers when subjected to acidic attack. This observation is true for 7 days, 28 days, and 90 days of flexural strength. The percentage increase in flexural strength after 7, 28, and 90 days at a 1.4% addition of steel fibers is found to be 78%, 76%, and 29%, respectively. This indicates that a small percentage addition of steel fibers can resist the acidic attack, thereby improving the flexural strength of HVFAC.

Table 13 gives the overall results of the impact strength of FRHVFAC. Additionally, it provides a percentage increase or decrease in split tensile strength compared to the reference mix. It is observed that the impact strength of FRHVFAC increases as the percentage of steel fibers in it increases up to 1.4% when subjected to acidic attack. After adding 1.4% steel fibers, the impact strength decreases. Thus, the higher value of impact strength may be obtained by using 1.4% steel fibers when subjected to acidic attack. This observation is true for 7 days, 28 days, and 90 days of impact strength. The percentage increase in impact strength after 7 days, 28 days, and 90 days, with a 1.4% addition of steel fibers, is found to be 210%, 205%, and 204%, respectively. This indicates that a small percentage addition of steel fibers can resist the acidic attack, thereby improving the impact strength of HVFAC.

The improvement in the properties of HVFAC subjected to acidic attack may be due to the fact that the addition of 1.4% fibers fills all the major voids, resulting in a dense mass. The addition of more than 1.4% steel fiber results in a decrease in the strength characteristics, as it significantly affects the workability of concrete. Mixing and compaction operations become difficult when more than 1.4% steel fibers are added to high-volume fly ash concrete. In addition to the pore-filling action of fly ash and its pozzolanic reaction, the fibers also contribute to the dense microstructure of concrete, thereby reducing the penetration of acidic ions. Substantial improvements are also found in tensile strength, flexural strength, and impact strength when 1.4% steel fibers are added to high-volume fly ash concrete.

Thus, there is a clear indication that the use of steel fibers in high-volume fly ash concrete can modify its properties, even in an acidic environment, making it suitable for rigid pavement construction.

6. Behaviour of FRHVAC Rigid Pavements Under Corner Loading, Edge Loading, and Center Loading Conditions

M40 concrete was designed according to CANMET guidelines with 50% replacement of cement by fly ash. The final mix proportion obtained was 1:1.17:2.54 (BC: FA: CA), incorporating a water–binder ratio of 0.30 and a superplasticizer dosage of 1.1% by weight of cementitious materials. An optimum fiber content of 1.4% by volume fraction, identified from earlier experimental investigations, was added to selected mixes. A rigid base was prepared and compacted with a road roller to ensure uniform reaction for all subgrade conditions. Slabs of size 1.5 m × 2.0 m × 0.10 m were cast on the prepared base, with three slabs produced without fibers and three with fibers. IPA strain gauges were embedded at critical strain locations for central, edge, and corner loading. A plastic sheet was placed beneath each slab to minimize friction and reduce moisture loss. Concrete constituents were batched, thoroughly mixed, carefully placed to avoid damaging the gauges, and compacted using a plate vibrator. After 28 days of curing, each slab was tested under gradually applied wheel loads using a 20-ton single-axle dual-tyre truck with a capacity of 20 tonnes. The load on the test wheel was monitored with a portable weighing machine, while strains were recorded continuously through a 10-channel strain indicator connected to

a computer.

Fig. 1 Preparation of the aggregate layer below the slab.

Fig. 2 Compaction of aggregate layer below the slab.

Fig. 3 Finished subgrade layer below the slab.

Table -6. Compressive strength outcomes of FRHVFAC

% of fiber	7 days CS (MPa)	% of variation wrt CC	28 days CS (MPa)	% of variation wrt CC	90 days CS (MPa)	% of variation wrt CC
0	19.56	-	43.33	-	51.11	-
0.20	20.00	2	44.74	3	52.74	0.20
0.40	20.78	6	46.07	6	54.37	d
0.60	21.33	9	47.41	9	56.00	10
0.80	22.26	14	49.19	14	58.22	14
1.00	22.74	16	50.37	16	59.41	16
1.20	22.89	17	50.37	16	59.70	17
1.40	22.96	17	50.96	18	60.00	17
1.60	22.67	16	50.37	16	59.41	16
1.80	22.59	16	50.22	16	59.26	16

Table -7. Split tensile strength outcomes of FRHVFAC

% of fiber	7 days STS (MPa)	% of variation wrt CC	28 days STS (MPa)	% of variation wrt CC	90 days STS (MPa)	% of variation wrt CC
0	1.74	-	2.35	-	3.30	-
0.20	1.86	7	2.65	13	3.30	0
0.40	1.91	9	2.74	17	3.37	2
0.60	2.02	16	2.83	21	3.54	7
0.80	2.09	20	3.02	29	3.57	8

1.00	2.22	27	3.17	35	3.62	10
1.20	2.32	33	3.27	39	3.8d	17
1.40	2.41	38	3.30	41	3.94	19
1.60	2.38	36	3.28	40	3.87	17
1.80	2.31	32	3.21	37	3.82	16

Table -8. Flexural strength outcomes of FRHVFAC

% of fiber	7 days FS (MPa)	% of variation wrt CC	28 days FS (MPa)	% of variation wrt CC	90 days FS (MPa)	% of variation wrt CC
0	2.21	-	3.37	-	5.77	-
0.20	2.77	25	4.20	25	6.29	9
0.40	3.07	39	4.63	38	6.64	15
0.60	3.15	42	4.96	47	7.05	22
0.80	3.43	55	5.18	54	7.11	23
1.00	3.81	72	5.77	71	7.13	24
1.20	3.84	73	5.87	74	7.32	27
1.40	3.97	80	5.99	78	7.44	29
1.60	3.93	78	5.94	76	7.40	28
1.80	3.87	75	5.91	76	7.37	28

Table - 9. Impact strength outcomes of FRHVFAC

% of fiber	7 days CS (MPa)	% of variation wrt CC	28 days CS (MPa)	% of variation wrt CC	90 days CS (MPa)	% of variation wrt CC
0	1348.61	-	2060.95	-	2458.71	-
0.20	2178.52	62	3326.56	61	3968.59	61
0.40	2558.90	90	3893.67	89	4645.15	89
0.60	3084.51	129	4682.09	127	5585.73	127
0.80	3561.71	164	5415.18	163	6460.30	163
1.00	3575.54	165	5435.92	164	6485.06	164
1.20	3969.75	194	6030.69	193	7194.62	193
1.40	4156.48	208	6293.50	205	7508.14	205
1.60	3872.92	187	5885.46	186	7021.35	186
1.80	3298.90	145	5014.05	143	5981.76	143

Table -10. Overall results of compressive strength for FRHVFAC when subjected to acidic attack.

% of fiber	7 days CS (MPa)	% of variation wrt CC	28 days CS (MPa)	% of variation wrt CC	90 days CS (MPa)	% of variation wrt CC
0	14.67	-	32.44	-	38.30	-
0.20	14.96	2	33.48	3	39.63	3
0.40	15.59	6	34.52	6	40.89	7
0.60	16.00	9	35.56	10	42.07	10
0.80	16.67	14	36.89	14	43.70	14
1.00	17.00	16	37.70	16	44.44	16
1.20	17.15	17	37.93	17	45.19	18
1.40	17.19	17	38.15	18	45.33	18
1.60	17.07	16	37.70	16	44.59	16
1.80	16.93	15	37.63	16	44.30	16

Table -11. Overall results of split tensile strength for FRHVFAC when subjected to acidic attack.

% of fiber	7 days STS (MPa)	% of variation wrt CC	28 days STS (MPa)	% of variation wrt CC	90 days STS (MPa)	% of variation wrt CC
0	1.30	-	1.73	-	2.48	-
0.20	1.39	7	1.98	14	2.52	2
0.40	1.44	11	2.05	18	2.53	2
0.60	1.51	16	2.12	22	2.65	7
0.80	1.57	21	2.26	31	2.68	8
1.00	1.66	28	2.37	37	2.71	10
1.20	1.70	31	2.44	41	2.89	17
1.40	1.82	40	2.53	46	2.94	19
1.60	1.78	37	2.50	44	2.90	17
1.80	I .74	35	2.46	42	2.82	14

Table -12. Overall results of flexural strength for FRHVFAC when subjected to acidic attack.

% of fiber	7 days FS (MPa)	% of variation wrt CC	28 days FS (MPa)	% of variation wrt CC	90 days FS (MPa)	% of variation wrt CC
0	1.65	-	2.53	-	4.33	-
0.20	2.08	26	3.15	25	4.73	9
0.40	2.29	39	3.47	37	4.99	15
0.60	2.36	43	3.71	47	5.29	22
0.80	2.57	56	3.88	54	5.33	23
1.00	2.85	73	4.33	71	5.36	24
1.20	2.92	77	4.41	75	5.49	27
1.40	2.95	78	4.45	76	5.59	29
1.60	2.89	75	4.41	75	5.48	26
1.80	2.84	72	4.37	73	5.39	24

Table -13. Overall results of impact strength for FRHVFAC when subjected to acidic attack.

% of fiber	7 days FS (MPa)	% of variation wrt CC	28 days FS (MPa)	% of variation wrt CC	90 days FS (MPa)	% of variation wrt CC
0	1009.73	-	1549.17	-	1818.89	-
0.20	1639.08	62	2496.65	61	2925.44	61
0.40	1915.71	90	2918.52	88	3416.47	88
0.60	2316.84	129	3520.21	127	4114.98	126
0.80	2676.47	165	4066.57	163	4758.16	162
1.00	2683.38	166	4080.40	163	4771.99	162
1.20	2980.77	195	4529.94	192	5304.52	192
1.40	3126.00	210	4723.58	205	5532.75	204
1.60	2911.61	188	4412.37	185	5166.20	184
1.80	2475.90	145	3762.27	143	4398.53	142

Table -14. Strains at the corner, edge, and center of the rigid pavement of HVFAC and FRHVFAC

Load (N)	Strains at the corner of the pavement		Strains at the edge of the pavement		Strains at the center of the pavement	
	HVFAC	FRHVFAC	HVFAC	FRHVFAC	HVFAC	FRHVFAC
15000	240	125	312	165	120	80
20000	532	394	634	445	8180	120
25000	714	486	784	527	242	162
30000	822	665	900	680	397	180
35000	913	735	982	768	412	264
40000	1215	878	1140	935	520	380
45000	1456	1123	1269	1083	603	391
50000	1855	1426	1485	1225	685	415
55000	2125	1895	1532	1312	732	472
60000	2542	2009	1795	1480	825	587
62500	3017	2285	-	-	-	-
65000	-	2456	1945	1623	934	633
70000	-	2978	2196	1845	1020	723
75000	-	3215	2516	2115	1112	845
80000	-	3410	-	-	-	-
81500	-	3525	-	-	-	-
85000	-	-	-	2308	1240	978
90000	-	-	-	2685	1319	1123
91000	-	-	-	2817	1482	1265
97500	-	-	-	-	1800	1419
100000	-	-	-	-	-	1595
105000	-	-	-	-	-	1985

7. CONCLUSIONS

1. The strength properties of FRHVFAC, such as compressive strength, tensile strength, flexural strength, and impact strength, have shown an increasing trend up to 1.4% with the addition of steel fibers. Thereafter, the strength properties show a decreasing trend. This is true for 7 days, 28 days, and 90 days of strength. Thus, the use of steel fibers in high-volume fly ash can modify the strength properties. Therefore, high-volume fly ash concrete can be recommended in the construction of rigid pavements.

2. FRHVFAC has shown better resistance to acidic attack by allowing less acid to penetrate. Substantial improvements are observed in compressive strength, tensile strength, flexural strength, and impact strength when 1.4% steel fibers are added to high-volume fly ash concrete, particularly under acidic attack conditions. Therefore, FRHVFAC can be recommended in the

construction of rigid pavement where acid attack possibilities exist.

3. The strength properties of FRHVFAC, such as compressive strength, tensile strength, flexural strength, and impact strength, have shown an increasing trend up to 1.4% addition of steel fibers, when subjected to sulphate attack of potassium sulphate solution of 15% concentration. A more than 1.4% addition of steel fibers results in a decrease in the strength values. Thus, substantial improvements are observed in compressive strength, tensile strength, flexural strength, and impact strength when 1.4% steel fibers are added to high-volume fly ash concrete, particularly under conditions of sulphate attack. Therefore, FRHVFAC can be recommended for constructing rigid pavements in soils affected by sulfates.

4. Remarkable improvements are also found in compressive strength, tensile strength, flexural strength, and impact strength when 4% steel fibers are added to high-volume fly ash concrete and when subjected to chloride attack. The strength characteristics have shown a decreasing trend after the addition of 1.4% steel fibers in high-volume fly ash concrete subjected to chloride attack. Thus, there is a clear indication that the use of steel fiber in high-volume fly ash concrete can modify the properties and allow fewer chloride ions to penetrate. Therefore, FRHVFAC can be recommended for the construction of rigid pavements where chloride attacks are a possibility.

5. The thermal conductivity of FRHVFAC shows a decreasing trend with an increase in fiber content up to 1.6%. More than 1.4% of fibers results in increased values of thermal conductivity. A similar observation is made with the coefficient of linear expansion, where the coefficient of linear expansion of FRHVFAC shows a decreasing trend with an increase in the fiber content up to 1.6%.

6. The tests on destructive loading on FRHVFAC rigid pavements reveal the fact that their load-carrying capacity is more than that of high-volume fly ash concrete rigid pavements. The corresponding strain values are also less in FRHVFAC pavements. Also, it is observed that the number of cracks, the width of cracks, and the length of cracks are much smaller in FRHVFAC pavements as compared to high-volume fly ash concrete pavements.

7. Thus, the study reveals the fact that the addition of steel fibers to high-volume fly ash concrete can enhance the properties of concrete and make it suitable for the construction of rigid pavements.

8. SCOPE FOR FUTURE WORK

The following works may be taken up in the future with respect to fiber-reinforced high-volume fly ash concrete.

1. To check the suitability of other fibers, such as GI fiber, waste HDPE fibers, plastic fibers, etc, in high-volume fly ash concrete for the construction of rigid pavements.
2. To check the suitability of hybrid fibers in high-volume fly ash concrete for the construction of rigid pavements.
3. To check the suitability of fiber-reinforced high-volume fly ash concrete for the construction of rigid pavements with a cement replacement level of more than 70%.
4. To find out the shrinkage behavior of fiber-reinforced high-volume fly ash concrete under different temperatures.
5. To find out the behavior of fiber-reinforced high-volume fly ash concrete under alternate wetting and drying.
6. To find out the behavior of fiber-reinforced high-volume fly ash concrete under freezing and thawing conditions.
7. To study the behavior of fiber-reinforced high-volume fly ash concrete pavement under dynamic loading.
8. To study the behavior of fiber reinforced high volume fly ash concrete under cyclic loading/fatigue loading.
9. To formulate a model for the behavior of fiber-reinforced high-volume fly ash concrete pavements under edge loading, corner load, and central loading.

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