

**PERFORMANCE ENHANCEMENT OF PAVEMENT
CONCRETE BY HYBRID FIBER INCLUSION
VIS-À-VIS SOLO FIBER**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

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Submitted

In fulfilment of the requirement for the degree of Doctor of Philosophy

to the



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CERTIFICATE

This is to certify that the thesis entitled “**PERFORMANCE ENHANCEMENT OF PAVEMENT CONCRETE BY HYBRID FIBER INCLUSION VIS-À-VIS SOLO FIBER**”, is being submitted by **Mr. Pankaj Goel**, to the **Indian Institute of Technology Delhi**, for the award of ‘**Doctor of Philosophy**’ in Department of Civil Engineering is a record of the bonafide research work carried out by him under my supervision and guidance. To the best of my knowledge, the thesis has reached the requisite standard. The material contained in the thesis has not been submitted, in part or full to any other University or Institute for the award of any other degree or diploma.



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Pankaj Goel

ABSTRACT

The concrete, which is used in the construction of pavements, overlay of bridge decks, airport runways etc., is commonly known as paving grade concrete. The paving grade concrete mixes (4.5 MPa and 6.2 MPa characteristic flexural strength) are widely used for the construction, repairs, rehabilitation and upgradation of the pavements. The design service life of these concrete pavements is mainly governed by their flexural behaviour under given traffic and environmental cyclic loading conditions. The large exposed surface area of concrete pavements makes them more susceptible to develop premature cracking due to shrinkage. Under the cyclic loading, progressive growth of existing micro-cracks occurs, further converting them into macro-cracks. The cracks reduce the durability and serviceability of concrete pavement, according to the severity levels of distresses in concrete pavements, maintenance, repair and rehabilitation are required. Repairing and rehabilitating the concrete pavement is a major issue, which is a time-consuming activity. Further, concrete pavements are also subjected to the rolling action of airborne particles, braking, skidding, accelerating and sliding of vehicle tires, which causes abrasion of the pavement surface.

The critical properties used in the design and maintenance of concrete pavements include flexural behaviour, strength and durability properties (in terms of drying shrinkage and abrasion resistance) in a tropical climate. In the last few decades, numerous attempts have been made to enhance the design service life, performance and delay the rehabilitation or reconstruction of concrete pavement by improving its relevant properties.

Modifying the internal structure of a concrete matrix by the inclusion of materials (viz., nanoparticles, micro-particles, structural fibers and their combinations) besides its basic ingredients (e.g. cement, aggregate and water) is one of the approaches adopted to improve the specific engineering properties of the concrete in fresh and hardened stages. A particular or solo fiber is used to enhance only some specific properties of the concrete composite, depending upon the fiber characteristics (e.g. material, type and features etc.). Generally, high modulus macro fiber is used to improve strength, deflection and flexural behaviour. In contrast, low modulus micro fiber is used to improve the shrinkage characteristic of concrete mix. A hybrid combination of two or more fibers has a better perspective for further enhancement in some of the specific properties beyond a particular benefit of different types of fibers.

The present study focuses on exploring the prospects of hybrid fiber reinforced paving grade concrete mixes in the construction of long-life, sustainable concrete pavements and their use as a durable overlay material for distressed concrete and flexible roads. An attempt has been made to obtain a synergic response from a hybrid combination of macro steel fiber and micro polypropylene fiber to improve the critical properties of paving-grade concrete mixes. Macro steel fibers of different lengths (35 mm to 60 mm), aspect ratios (50 to 65) and shapes (crimped and hooked end) were used. Micro polypropylene fibers (monofilament) of different lengths (6 mm and 18 mm) and a micro polypropylene fibrillated fiber of 18 mm in length were used. The crushed stone aggregate of the maximum size of 25 mm and 12.5 mm was used to prepare the paving-grade concrete mixes of 4.5 MPa and 6.2 MPa characteristic flexural strength respectively. Reddish land quarried sand known as 'Badarpur sand' was used as fine aggregate. The poly-carboxylate ether-based (PCE) superplasticizer was used to achieve the desired properties of the concrete mixes. The effectiveness of steel fiber in a concrete composite depends on the fiber's bond with the concrete matrix, which is governed by the concrete microstructure and properties of the Interfacial Transition Zone (ITZ). The 'Class F' fly ash and silica fume were used to improve the concrete microstructure and the properties of ITZ. Several trial mixes were made before finalizing the paving-grade fiber-reinforced concrete mixes. The critical fiber content for steel fiber was determined theoretically for more than 15% enhancement in flexural strength of steel fiber-reinforced concrete (SFRC). The volumetric fraction was estimated and found between 0.33% to 0.53% for both the concrete mixes. Further, experimentally three different volumetric fractions (0.25%, 0.5% and 0.75%) were used to verify it. The optimized volumetric fraction of steel fiber was 0.5% for both the paving grade concrete mixes. The polypropylene fiber dosage was optimized for more than a 20% reduction in drying shrinkage and abrasion loss of synthetic fiber reinforced concrete (SyFRC). The optimized volumetric fraction of polypropylene fibre was 0.1%. Then using these optimum fiber content, a total of 810 concrete specimens from 18 concrete mixes (9 concrete mixes from each combination, i.e., 4.5 MPa and 6.2 MPa) were cast. Each combination included control concrete (without fiber), three SyFRC, two SFRC and three Hybrid fiber-reinforced concrete (HyFRC) mixes. As per the IRC-15: 2017, the concrete pavements are designed for a deflection of 1.25 mm and the post-peak flexural behaviour of composite concrete specimens (in terms of toughness indices and residual strength factors) was investigated as per ASTM C 1018-97. At the same time, other key features of paving grade concrete, such as impact resistance (ACI 544.2R: 89) and durability properties in terms of drying shrinkage (IS-1999:1959) and abrasion resistance (ASTM C799-10), were also

investigated. Further, the strength properties of concrete mixes (flexural and compressive strength (IS-516: 2000) and splitting tensile strength (IS-586: 1970) were also studied.

The study concludes that the inclusion of synthetic fiber alone in concrete does not contribute to flexural behaviour enhancement. However, its small dosage in a hybrid system synergizes the efficiency of steel fiber. All the SyFRC and SFRC concrete mixes had deflection-softening behaviour similar to the control concrete. In contrast, in some cases HyFRC concrete mixes had a deflection-hardening behaviour. Further, the concrete reinforced by hybrid fibers also witnessed a significant improvement in toughness indices (up to 14-fold) and residual strength factors (37-74 units more than control concrete). The concrete reinforced by hybrid fiber had the maximum enhancement in flexural strength (20-30%) as compared to the control concrete, which was more than individual fibers. However, the concrete reinforced by hybrid fiber was observed to have almost a similar split tensile strength as steel fiber alone. Further, it was also observed that the HyFRC and SFRC specimens didn't separate even after their failure. The inclusion of synthetic fibers did not influence impact resistance. However, the hybridization of polypropylene-steel fiber significantly improved the impact resistance (up to 27-fold) which was more than steel fiber as alone.

The present study also revealed that the hybrid combination of synthetic and steel fiber can carry the residual strength for a more extended time even after the first crack or failure of the concrete matrix. The HyFRC mixes had a maximum reduction in drying shrinkage (up to 63%), followed by SyFRC (up to 37%) and SFRC (up to 22%) mixes, respectively. It was also observed that the HyFRC mix had a maximum reduction in abrasion depth (up to 31%), followed by SyFRC (up to 30%) and SFRC mix (up to 20%) as compared to the control concrete. Based on these observations and analysis of results, the study suggests a possible reduction in pavement slab thickness with enhanced features such as improved crack resistance under dynamic loading conditions, strength properties and durability properties. The study concluded that the hybridization of hooked end steel fiber and polypropylene fiber performed the best. The present study also suggests that suitable HyFRC mixes should be encouraged in the construction, repair and rehabilitation of concrete pavements, bridge deck overlays and airfield pavements, which are likely to be subjected to heavy truck loads with high traffic density.

सारांश

वह कंक्रीट, जिसका उपयोग सड़कों के निर्माण, उन्नयन, पुलों के डेक के ओवरले, हवाई अड्डों के रनवे आदि में किया जाता है, को आमतौर पर पेविंग-ग्रेड कंक्रीट के रूप में जाना जाता है। सड़कों के निर्माण, उन्नयन, मरम्मत, पुनर्वास और उन्नयन के लिए पेविंग-ग्रेड कंक्रीट मिश्रण (4.5 एमपीए और 6.2 एमपीए विशेषता फ्लेक्सुरल ताकत) का व्यापक रूप से उपयोग किया जाता है। इन कंक्रीट सड़कों का डिज़ाइन सेवा-जीवन मुख्य रूप से दिए गए यातायात और पर्यावरणीय साइक्लिक लोडिंग स्थितियों के तहत उनके फ्लेक्सुरल व्यवहार से नियंत्रित होता है। कंक्रीट सड़कों का बड़ा खुला सतह क्षेत्र इनको सिकुड़ने के कारण समय से पहले टूटने के प्रति अधिक संवेदनशील बनाता है। डायनैमिक साइक्लिक लोडिंग के तहत, मौजूदा माइक्रो-क्रैक की प्रगतिशील वृद्धि होती है, जो आगे चलकर उन्हें मैक्रो-क्रैक में परिवर्तित कर देती है। ये दरारें कंक्रीट सड़कों के स्थायित्व और सेवाक्षमता को कम कर देती हैं, कंक्रीट सड़कों में डिस्ट्रेसेस की गंभीरता के स्तर के अनुसार रखरखाव, मरम्मत और पुनर्वास की आवश्यकता होती है। परंतु कंक्रीट सड़कों की मरम्मत और पुनर्वास एक प्रमुख मुद्दा है, जो एक समय लेने वाली और खर्चीली प्रक्रिया है। इसके अलावा, कंक्रीट की सड़के हवा में उड़ने वाले कणों के लुढ़कने, वाहन के टायरों के ब्रेक लगाने, फिसलने, और तेज होने के अधीन होते हैं, जिससे सड़कों की सतह पर घर्षण होता है।

कंक्रीट सड़कों के डिज़ाइन और रखरखाव में उपयोग किए जाने वाले महत्वपूर्ण गुणों में उष्णकटिबंधीय जलवायु में फ्लेक्सुरल व्यवहार, ताकत और स्थायित्व गुण (सूखने के कारण सिकुड़ने और घर्षण प्रतिरोध के संदर्भ में) शामिल हैं। पिछले कुछ दशकों में, डिज़ाइन सेवा-जीवन और प्रदर्शन को बढ़ाने और इसके प्रासंगिक गुणों में सुधार करके कंक्रीट सड़कों के पुनर्वास या पुनर्निर्माण में देरी करने के लिए कई प्रयास किए गए हैं।

कंक्रीट मैट्रिक्स की आंतरिक संरचना को इसके मूल अवयवों (जैसे सीमेंट, एग्रीगेट और पानी) के अलावा अन्य सामग्रियों (जैसे, नैनोकण, सूक्ष्म कण, संरचनात्मक फाइबर और उनके संयोजन) को शामिल करके संशोधित करना, सुधार के लिए अपनाए गई प्रमुख विधियों में से एक है। एक विशेष या एकल फाइबर

का उपयोग कंक्रीट मिश्रित के केवल कुछ विशिष्ट गुणों को बढ़ाने के लिए किया जाता है, जो फाइबर विशेषताओं (जैसे सामग्री, प्रकार और विशेषताएं आदि) पर निर्भर करता है। आम तौर पर, उच्च मापांक (हार्ड-मॉड्यूलस) मैक्रो फाइबर का उपयोग ताकत, विक्षेपण और फ्लेक्सुरल व्यवहार में सुधार के लिए किया जाता है। इसके विपरीत, कंक्रीट मिश्रण की सिकुड़न विशेषता को बेहतर बनाने के लिए कम मापांक (लो मॉड्यूलस) वाले सूक्ष्म फाइबर का उपयोग किया जाता है। दो या दो से अधिक रेशों का एक संकर संयोजन विभिन्न प्रकार के रेशों के एक विशेष लाभ से परे कुछ विशिष्ट गुणों में और अधिक वृद्धि के लिए बेहतर परिप्रेक्ष्य रखता है।

वर्तमान अध्ययन लंबे समय तक चलने वाली, टिकाऊ कंक्रीट सड़कों के निर्माण में हाइब्रिड फाइबर प्रबलित पेविंग-ग्रेड कंक्रीट मिश्रण की संभावनाओं को खोजने और संकटग्रस्त कंक्रीट सड़कों के लिए टिकाऊ ओवरले सामग्री के रूप में उनके उपयोग पर केंद्रित है। पेविंग-ग्रेड कंक्रीट मिश्रण के महत्वपूर्ण गुणों में सुधार करने के लिए मैक्रो स्टील फाइबर और माइक्रो पॉलीप्रोपाइलीन फाइबर के हाइब्रिड संयोजन से एक सहक्रियात्मक प्रतिक्रिया प्राप्त करने का प्रयास किया गया है। विभिन्न लंबाइयों (35 मिमी से 60 मिमी), ऐस्पेक्ट अनुपातों (50 से 65) और आकारों (क्रिम्पड और हुकड-एंड) वाले मैक्रो स्टील फाइबर का उपयोग किया गया था। विभिन्न लंबाई (6 मिमी और 18 मिमी) के माइक्रो पॉलीप्रोपाइलीन फाइबर (मोनोफिलामेंट) और 18 मिमी लंबाई के माइक्रो पॉलीप्रोपाइलीन फाइब्रिलेटेड फाइबर का उपयोग किया गया था। 25 मिमी और 12.5 मिमी के अधिकतम आकार के पत्थर समुच्चय का उपयोग क्रमशः 4.5 एमपीए और 6.2 एमपीए विशेषता फ्लेक्सुरल ताकत के पेविंग-ग्रेड कंक्रीट मिश्रण तैयार करने के लिए किया गया था। भूमि से निकाली गई रेत जिसे 'बदरपुर रेत' के नाम से जाना जाता है, का उपयोग बारीक समुच्चय के रूप में किया गया था। कंक्रीट मिश्रण के वांछित गुणों को प्राप्त करने के लिए पॉली-कार्बोक्सिलेट ईथर-आधारित (पीसीई) सुपरप्लास्टीसाइजर का उपयोग किया गया था। कंक्रीट मिश्रण में स्टील फाइबर की प्रभावशीलता कंक्रीट मैट्रिक्स के साथ फाइबर के बंधन पर निर्भर करती है, जो कंक्रीट माइक्रोस्ट्रक्चर और इंटरफेशियल ट्रांजिशन जोन (आईटीजेड) के गुणों द्वारा नियंत्रित होती है। कंक्रीट माइक्रोस्ट्रक्चर और आईटीजेड के गुणों को बेहतर बनाने के लिए 'क्लास-एफ' फ्लाई ऐश और सिलिका फ्यूम का उपयोग किया गया था। पेविंग-ग्रेड फाइबर-प्रबलित कंक्रीट मिश्रण को अंतिम रूप देने से पहले कई परीक्षण मिश्रण बनाए गए थे। स्टील फाइबर-प्रबलित कंक्रीट (एसएफआरसी) की फ्लेक्सुरल

ताकत में 15% से अधिक वृद्धि के लिए स्टील फाइबर के लिए महत्वपूर्ण फाइबर सामग्री सैद्धांतिक रूप से निर्धारित की गई थी। सैद्धांतिक रूप से दोनों कंक्रीट मिश्रणों के लिए वॉल्यूमेट्रिक अंश का अनुमान 0.33% से 0.53% के बीच पाया गया। इसके अलावा, इन वॉल्यूमेट्रिक आंशिक अनुमानों को सत्यापित करने के लिए प्रयोगात्मक रूप से तीन अलग-अलग वॉल्यूमेट्रिक अंशों (0.25%, 0.5% और 0.75%) का उपयोग किया गया था। दोनों पेविंग-ग्रेड कंक्रीट मिश्रणों के लिए स्टील फाइबर का अनुकूलित वॉल्यूमेट्रिक अंश 0.5% था। सिंथेटिक फाइबर प्रबलित कंक्रीट (SyFRC) के सूखने के संकोचन और घर्षण हानि में 20% से अधिक की कमी के लिए पॉलीप्रोपाइलीन फाइबर की खुराक को अनुकूलित किया गया था। पॉलीप्रोपाइलीन फाइबर का अनुकूलित वॉल्यूमेट्रिक अंश 0.1% था। फिर इन इष्टतम फाइबर सामग्री का उपयोग करके, 18 कंक्रीट मिश्रणों (प्रत्येक संयोजन से 9 कंक्रीट मिश्रण, यानी, 4.5 एमपीए और 6.2 एमपीए) से कुल 810 विभिन्न आकारों वाले कंक्रीट नमूने तैयार किए गए। प्रत्येक संयोजन में नियंत्रण कंक्रीट (फाइबर के बिना), तीन SyFRC, दो SFRC और तीन हाइब्रिड फाइबर-प्रबलित कंक्रीट (HyFRC) मिश्रण शामिल थे। आईआरसी-15: 2017 के अनुसार, कंक्रीट फुटपाथ 1.25 मिमी के विक्षेपण के लिए डिज़ाइन किए गए हैं और मिश्रित कंक्रीट नमूनों के शिखर के बाद के लचीले व्यवहार (कठोरता सूचकांक और अवशिष्ट ताकत कारकों के संदर्भ में) की जांच एएसटीएम सी 1018 के अनुसार की गई थी। उसी समय, पेविंग ग्रेड कंक्रीट की अन्य प्रमुख विशेषताएं, जैसे इम्पैक्ट प्रतिरोध (एसीआई 544.2आर: 89), सुखाने के संकोचन (आईएस-1999:1959) और घर्षण प्रतिरोध (एएसटीएम-सी799-10) के संदर्भ में स्थायित्व गुणों की जांच भी की गई, इसके अलावा, कंक्रीट मिश्रण की ताकत के गुणों (फ्लेक्सुरल और कंप्रेसिव स्ट्रेंथ (आईएस-516: 2000) और स्प्लिटिंग टेन्साइल स्ट्रेंथ (आईएस-586: 1970) का भी अध्ययन किया गया।

किए गए अध्ययन से यह निष्कर्ष निकलता है, कि कंक्रीट में अकेले सिंथेटिक फाइबर को शामिल करने से लचीले व्यवहार में वृद्धि में कोई योगदान नहीं होता है। हालाँकि, हाइब्रिड प्रणाली में इसकी छोटी खुराक स्टील फाइबर की दक्षता को बढ़ा देती है। सभी SyFRC और SFRC कंक्रीट मिश्रणों में नियंत्रण कंक्रीट के समान विक्षेपण-नरम व्यवहार था। इसके विपरीत, कुछ मामलों में HyFRC कंक्रीट मिश्रण में विक्षेपण-सख्त व्यवहार था। इसके अलावा, हाइब्रिड फाइबर द्वारा प्रबलित कंक्रीट में कठोरता सूचकांक (14 गुना तक) और अवशिष्ट ताकत कारकों (कंट्रोल कंक्रीट से 37-74 यूनिट अधिक) में भी महत्वपूर्ण

सुधार देखा गया। हाइब्रिड फाइबर द्वारा प्रबलित कंक्रीट में कंट्रोल कंक्रीट की तुलना में फ्लेक्सुरल ताकत (20-30%) में अधिकतम वृद्धि हुई थी, जो व्यक्तिगत फाइबर से अधिक थी। हालाँकि, हाइब्रिड फाइबर द्वारा प्रबलित कंक्रीट में अकेले स्टील फाइबर के समान ही विभाजित तन्य शक्ति देखी गई। इसके अलावा, यह भी देखा गया कि HyFRC और SFRC नमूने अपनी विफलता के बाद भी अलग नहीं हुए। सिंथेटिक फाइबर को शामिल करने से इम्पैक्ट प्रतिरोध पर कोई प्रभाव नहीं पड़ा। हालाँकि, पॉलीप्रोपाइलीन-स्टील फाइबर के संकरण से प्रभाव प्रतिरोध में काफी सुधार हुआ (27 गुना तक) जो अकेले स्टील फाइबर से अधिक था।

वर्तमान अध्ययन से यह भी पता चला है कि सिंथेटिक और स्टील फाइबर का हाइब्रिड संयोजन कंक्रीट मैट्रिक्स की पहली दरार या विफलता के बाद भी अवशिष्ट ताकत को अधिक विस्तारित समय तक बनाए रख सकता है। HyFRC मिश्रण में सुखाने की सिकुड़न में अधिकतम कमी (63% तक) थी, इसके बाद क्रमशः SyFRC (37% तक) और SFRC मिश्रण (22% तक) थे। यह भी देखा गया कि नियंत्रण कंक्रीट की तुलना में HyFRC मिश्रण में घर्षण गहराई में अधिकतम कमी (31% तक), इसके बाद SyFRC (30% तक) और SFRC मिश्रण (20% तक) थी। इन अवलोकनों और परिणामों के विश्लेषण के आधार पर, गतिशील लोडिंग स्थितियों, ताकत गुणों और स्थायित्व गुणों के तहत बेहतर दरार प्रतिरोध जैसी उन्नत सुविधाओं के साथ सड़कों के स्लैब की मोटाई में संभावित कमी का सुझाव देता है। अध्ययन ने यह भी निष्कर्ष निकाला है कि हुकड एंड स्टील फाइबर और पॉलीप्रोपाइलीन फाइबर के संकरण ने सबसे अच्छा प्रदर्शन किया। वर्तमान अध्ययन यह भी सुझाव देता है कि कंक्रीट सड़कों, ब्रिज डेक ओवरले और एयरफील्ड सड़कों के निर्माण, मरम्मत और पुनर्वास में उपयुक्त HyFRC मिश्रण को प्रोत्साहित किया जाना चाहिए, जो उच्च यातायात घनत्व के साथ भारी ट्रक लोड के अधीन होने की संभावना है।

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LIST OF NOTATIONS

μm	Micron meter
cm	Centimeter
mm	Millimeter
MPa	Mega Pascal (Newton/ mm^2)
GPa	Gega Pascal
kg	Kilogram
A	Cross- sectional area
A_c, A_f, A_m	Cross- sectional area of composite, fiber and matrix
l_c	Critical length of fiber
l_a	length of the fiber
d_f	Diameter of the fiber
l/d_f	Aspect ratio
$D_f,$	Density of fiber, matrix
ϵ	Strain
$\epsilon_c, \epsilon_f, \epsilon_m$	Strain in composite, fiber & matrix
ϵ_{mu}	Ultimate cracking strain in the Matrix
ϵ_{fu}	Ultimate strain in fiber
ϵ_{comp}	Compressive strain
ϵ_t	Tensile Strain
ϵ_x	Strain at the start of major multiple cracking
$\sigma_c, \sigma_f, \sigma_m$	Stress in composite, fiber & composite

σ_{mu}	Ultimate tensile stress of matrix or matrix cracking stress
σ_{MR}	Moment of resistance or Modulus of rupture of composite
σ_{cu}	Ultimate post cracking tensile strength of the composite
σ_{fu}	Failure stress of fully bonded fibers or pull-out stress of debonded fibers
E_c, E_f, E_m	Modulus of elasticity of composite, fiber & matrix
V_c, V_f, V_m	Volume of composite, fiber, matrix
V_f (crit)	Critical Volume of fiber
τ_{fu}	Shear bond strength
η_l, η_2	Fiber efficiency factor for orientation and length
τ	Maximum shear stress
x^1	Distance at which load is transferred or minimum crack spacing
α	Scaling factor ($\alpha = [(E_m/E_f) * (V_m/V_f)]$)
w	Crack width
x_d	Distance from the first crack
N	Number of fibers per unit area
τ	frictional bond strength
kN	Kilo newton
$m.s.a.$	Nominal maximum size of aggregate