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Environmental and economic benefits of steel, glass, and polypropylene fiber reinforced cement composite application in jointed plain concrete pavement

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ABSTRACT

Conventional plain concrete (PC) leads to large design thickness when used in applications where high flexural strength is required. Therefore, to minimize the consumption of natural resources and to avoid large design thickness, it is fundamental to upgrade the flexural strength of PC by using supplementary materials i.e. steel rebars, fibers. This study evaluated the environmental and economic performance of the pavements designed with different fibrous concrete composites (FCCs). FCCs were manufactured by incorporating 0.5 and 1.0% volume fractions of glass fiber (GF), hooked steel fiber (HSF), and polypropylene fiber (PPF) in the normal strength concrete (C30). Initially, the flexural properties of FCCs were evaluated and then these properties were utilized to design the thickness of jointed plain concrete pavement (JPCP). Using the cost and carbon emissions per cubic meter of each concrete mix, the environmental and economic performance of JPCP construction was estimated. The performance of different FCCs in the JPCP was compared with that of the conventional PC. The results of mechanical testing showed that HSF-FCC outperforms both PPF-FCC and GF-FCC by a significant margin. Despite inferior mechanical performance compared to HSF-FCC, both PPF-FCC and GF-FCC are very effective in reducing the carbon footprint and cost of JPCP. JPCPs with GF-FCC and PPF-FCC are also ecofriendly and economical than the JPCP with conventional PC for the same load-carrying capacity. Overall, FCC can yield cheaper and eco-friendlier pavements compared to conventional PC if the dosage and type of fiber are correctly chosen as recommended in this study.

1. INTRODUCTION

Conventional plain concrete (PC) despite high brittleness is the most widely used construction material on earth. Brittleness of PC increases with the increment in strength [1]. Under tension or flexural loadings, its strength is less than 12% of its compressive strength [2,3]. In structural applications where high flexural strength and toughness are required such as rigid pavements, PC due to its very low ductility requires a large thickness to meet the design needs. In rigid pavements, to avoid a large design thickness, steel rebars are conventionally used. Another approach to avoid the large structural dimensions is by increasing the flexural capacity of PC using a suitable fiber-reinforcement [4]. Fibrous concrete composites (FCCs) have many advantages over conventional steel rebar reinforced concretes such as the better distribution of reinforcement in the whole matrix of concrete, reduced tensile cracking, and a significant increase in both compression and flexural toughness [5–10]. FCCs also have high durability under extreme environmental conditions i.e. freeze-thaw cycles, acid attacks, chloride mediums, seawater environments, etc. [3,8,11–15].

Various types of fibers are being used in the construction industry such as steel, glass, polypropylene, carbon, basalt fibers, cork fiber, cardboard fibers, etc. and properties of concretes with these types of fibers have evaluated widely [16–24]. Due to very high tensile strength and elastic modulus, fiber-reinforcement can boost the power of the binder matrix of concrete to contain the tensile or flexural cracks that ultimately improves the flexural capacity of material [3,25]. Hooked

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steel fiber (HSF) incorporation can increase the flexural strength of concrete by more than 80% [8,26]. Glass fiber (GF) incorporation at 0.25–0.5% volume fractions leads to an increment of 25–29% in the flexural strength [27]. Similarly, polypropylene fiber (PPF) advances the tensile strength of PC by 20% [23]. A review of various studies in literature reveals that fibers are only effective in advancing the flexural and tensile strength of concrete and no noticeable advancement in compressive strength can be achieved with fibers [23,28]. This implies that fiber-reinforced concretes can only be helpful economically in applications where high flexural strength is required such as slabs on grounds, runaways, parking, linings of the tunnel, etc. [29].

Jointed plain concrete pavement (JPCP) is an important part of public infrastructure i.e. business streets, collector streets, industrial streets, minor and major arterials. It is well known that incorporating fibers enhances the flexural strength of composite, but a very few studies [30,31] are available in the literature which explore and compare the effects of different fibers on the design thicknesses of pavements under the same conditions of traffic loadings and subgrade conditions. Furthermore, no research is available which compares the benefits of different types and doses of fiber considering the economic and environmental impacts of FCC application in concrete pavements. The information in this regard is necessary for the selection of suitable type of fiber-reinforcement for the optimum mechanical benefits with minimum cost and carbon footprint. Therefore, this short communication aims to analyze the cost and carbon footprint of JPCP with different types of fibers i.e. HSF, GF, and PPF. For this purpose, initially, the mechanical properties (flexural strength and residual strength) of FCCs were evaluated. Then considering the same service conditions (traffic category, truck loading, subgrade properties, etc.) design thickness of JPCP was evaluated for FCC and conventional plain concrete (PC) following the Portland Cement Association (PCA) mechanistic design method for concrete pavements [32]. Cost and carbon footprint (CO_2) of JPCP per unit area was estimated for all the mixes under the same design conditions and the results were compared to evaluate the impacts of FCC application in pavement structures w.r.t conventional PC.

2. MATERIALS and methods

2.1. Materials

General purpose, Portland cement of Type I conforming to ASTM C150 [33] was used as the binder. Type I. This type of cement is the most common binder used in the construction of concrete pavements worldwide. Crushed limestone and siliceous sand were used as fine and coarse aggregates, respectively. Crushed limestone is sourced from a quarry of Margalla Hills, Taxila, Pakistan. Whereas, siliceous sand is sourced from Lawrancepur quarry in Attock, Pakistan. Basic properties of these aggregates are given in Table 1. Gradation of aggregates is within the limits of ASTM C33 [34] set for construction aggregates. Properties fiber reinforcements i.e. HSF, GF, and PPF are shown in Table 2. Overview of fibers is shown in Fig. 1.

2.2. Composition and manufacturing details of composites

Mix design of normal strength concrete performing cylindrical compressive strength of 30 MPa was prepared following ACI 211.1-9 [35]. In this concrete, two different dosages (0.5 and 1% volume fraction) of HSF, GF, and PPF were used to make FCCs. 50 mm slump was chosen for the workability that is normally preferred for placing concrete in the rigid pavements. In FCCs, workability loss due to fibers was compensated using a superplasticizer (SP) (Sika Viscocrete 3110). Details of all composites are provided in Table 3.

Table 1
Properties of aggregate.

Property	Fine aggregate	Coarse Aggregate
Material type	Siliceous sand	Limestone
Water absorption (%)	1.13	0.75
Max. particle size (mm)	4.75	25
Fineness modulus	2.54	–
Specific Gravity	2.67	2.65
Dry Rodded Density (kg/m^3)	1620	1540

Table 2
Properties of fibers.

Property	HSF	GF	PPF
Length (mm)	35	6–18	12
Diameter of filament (μm)	900	15	30
Tensile strength (MPa)	1200	1500–1700	500
Elastic modulus (GPa)	200	72	5
Density (kg/m^3)	7750	2600	900

SF: Steel fibers; **GF:** Glass fibers; **PPF:** Polypropylene fibers.

All mixes were prepared in a mechanical mixer with adjustable rotational speed. Firstly, aggregates and cement were dry blended at the speed of 40 rpm for 2 min. Then, half amount of water was added to the mix and blending continued at 60 rpm for 2 min. Subsequently, remaining half amount of water and superplasticizer were added to the mixture and blending continued at 60 rpm for 4 min. During the last stage, fibers were added to the mix and blending was done at a rapid speed of 80 rpm for 2 min. Then, until the finishing of casting of specimens, blending was continued at 40 rpm.

2.3. Evaluation of flexural behavior of composites

For flexural testing, specimens of 100 mm × 100 mm x 350 mm were tested following ASTM C78 [36] as shown in Fig. 2. The load-deflection behavior of these prismatic specimens was evaluated according to ASTM C1609 [37]. Load deflection data was used to calculate the flexural toughness and residual strength. Both flexural and residual strength are used in the thickness design of JPCP following PCA mechanistic design method [32].

2.4. Thickness design of pavement

Using the mechanical properties (flexural strength and residual strength as per ASTM C78) of each composite, thickness of jointed plain concrete pavement (JPCP) was designed for Major Arterial street (it has the highest truck traffic). All design input parameters are given in Tables 4 and 5. While designing the pavement thickness, all general design inputs were kept the same for all composites except mechanical properties [32].

2.5. Economic and environmental analysis of pavement for different mixes

To evaluate the economic performance of pavement with different mixes, firstly, the cost per unit volume of each concrete mix was calculated using the unit costs of its raw materials given in Table 6. In the cost of concrete mix, 20 USD per cubic meter was added as the charges for mixing, transporting, and placing concrete. Then using the cost of mixes, the cost per square meter of pavement was calculated using Eq. (1). Normally, for cost estimation of highway projects, cost per square meter of pavement is used. Therefore, the economic performance of pavements with different types of composite materials can be best compared by evaluating the cost of pavement per unit area under the same service conditions.

While energy emission and consumption in a highway facility is mostly related to the burning of gasoline through the automobiles, construction of pavement facility is also a huge cause for significant energy consumption and greenhouse gas emissions. Therefore, to

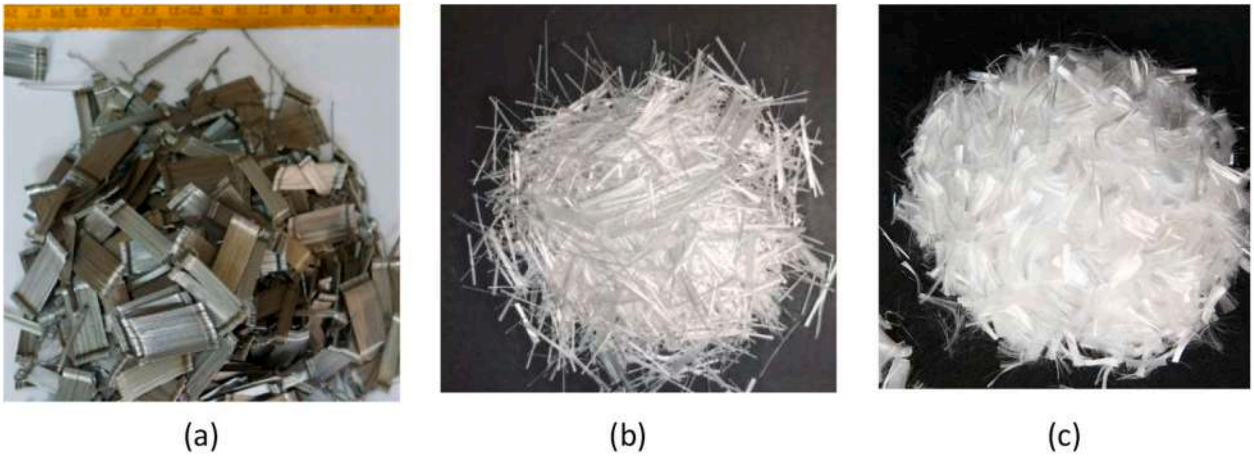


Fig. 1. Overview of **(a)** HSF **(b)** GF, and **(c)** PPF.

Table 3
Details of concrete mixes.

Mix IDs	Cement (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	SP (kg/m^3)	HSF (kg/m^3)	GF (kg/m^3)	PPF (kg/m^3)
PC	330	180	1076	796	0	0	0	0
FCC-0.5%HSF	330	180	1070	790	3.4	39	0	0
FCC-1%HSF	330	180	1063	783	4.5	78	0	0
FCC-0.5%GF	330	180	1070	790	3.4	0	13	0
FCC-1%GF	330	180	1063	783	4.5	0	26	0
FCC-0.5%PPF	330	180	1070	790	3.4	0	0	4.5
FCC-1%PPF	330	180	1063	783	4.5	0	0	9

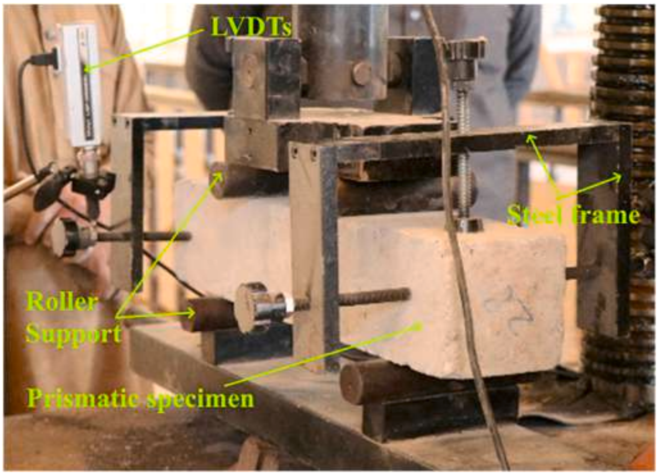


Fig. 2. Experimental test setup for third-pointed bending test.

Table 4
Traffic category and truckload.

Input	Street 2
Traffic Spectrum[a]	Major Arterial
Trucks/day	1500
Traffic growth	2%
Design life	30 Years
Directional distribution	50%
Design lane distribution	100%
Average trucks/day in design lane over the design life	1014
Total trucks on design lane over the design life	11,113,118

[a] Load spectrums for these traffic categories are given in PCA mechanistic design guidelines [32].

Table 5
Global design inputs and properties of subgrade and concrete.

Global design inputs	
Terminal serviceability	2
Reliability	85%
Resilient modulus of subgrade reaction	28 MPa
Slab cracked at the end of design life	15%
Composite modulus of subgrade reaction	28 MPa
Edge-support	Provided (at both sides)
Concrete material properties	
Flexural strength or Modulus of rupture (MPa)	Different for all mixes
Residual strength (%)	Different for FCCs 0% for PC[a]
Macro-fibers	Considered for FCC No for PC

[a] PC: Plain concrete mixes.

determine the environmental impact of pavement with different types of mixes, firstly, carbon emission per unit volume of each mix was calculated using the per-unit emissions of its raw materials provided in Table 6. Then, carbon emissions per square meter of the pavement for different mixes was calculated using Eq. (2). Environmental impact of pavement for different types of mixes can be fairly assessed using Eq. (2).

$$CP = COST_{MIX} \times h_{Design} \tag{1}$$

$$CEP = CE_{MIX} \times h_{Design} \tag{2}$$

where.

CP = Cost of pavement per square meter (USD/m^2)
COST$_{MIX}$ = cost of each concrete composite per cubic meter (USD/m^3)
h$_{Design}$ = Design thickness of pavement for a concrete composite (m)
CEP = Carbon emissions (CO$_2$) of pavement per square meter (CO$_2$/m^2)

Table 6

Cost and emission of raw materials per unit production.

Material	USD/kg	CO_2 (kg/kg)
Portland cement	0.1344	0.92 [38]
Quarry sand	0.0065	0.0015 [38]
Crushed limestone	0.0109	0.0285 [38]
HSF	0.8	2.65 [30]
GF	0.75	2.04 [39]
PPF	0.9	1.85 [39]
Water	0.0009	0
Superplasticizer	1.45	0.00181 [38]

CE_{MIX}= Carbon emissions (CO_2) of concrete composite mix per cubic meter (CO_2/m^3)

3. RESULTS and discussion

3.1. Flexural behavior of composites with different fibers

3.1.1. Flexural strength

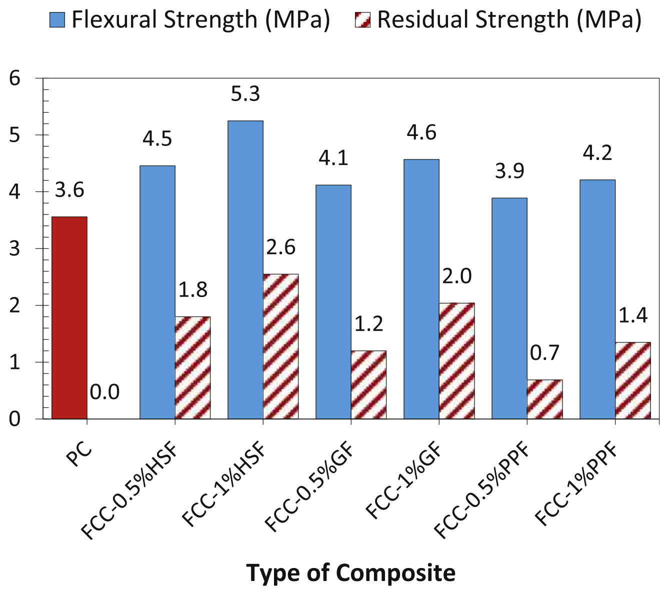
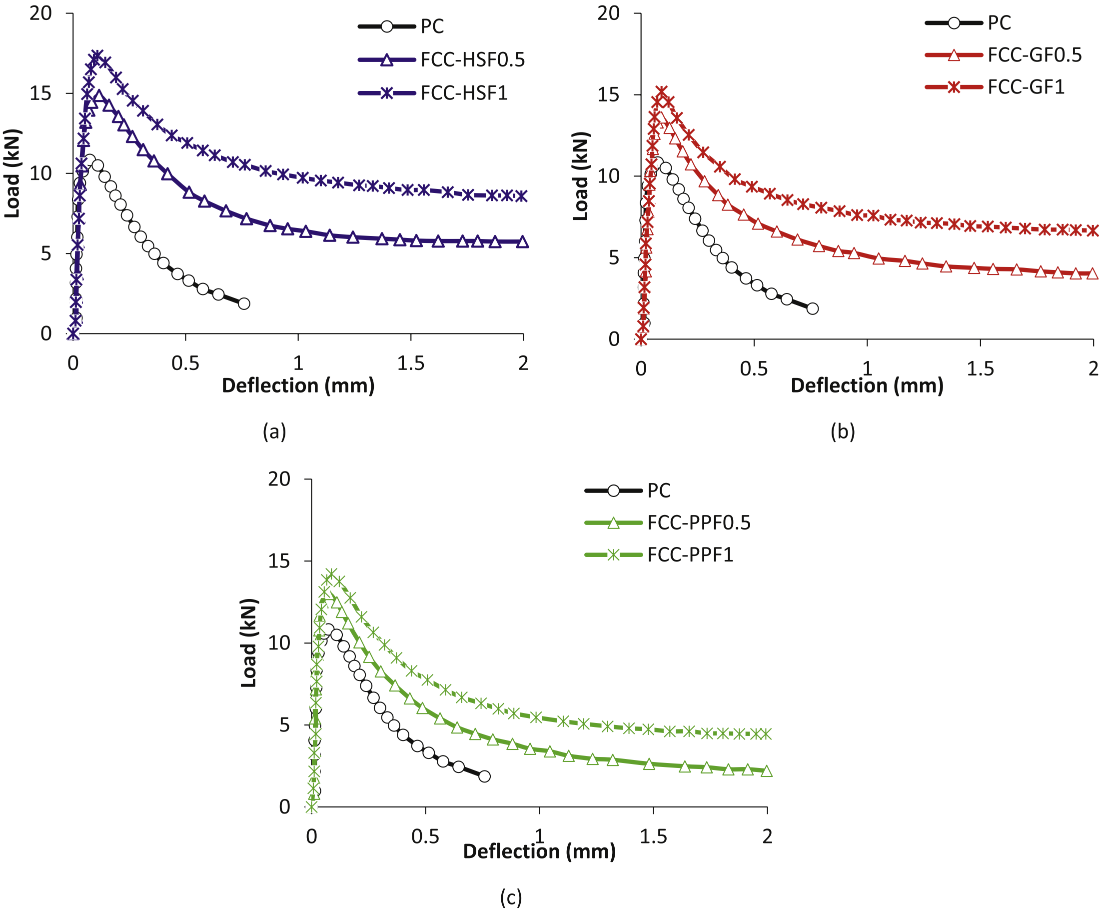


Fig. 4. (a) Flexural strength and (b) residual flexural strength of all composites.

Load-deflection data for all composites is plotted in Fig. 3 under a third-point flexural test following ASTM C78 and C1609 [36,37]. Flexural strength calculated using the peak load on the specimen from load-deflection data is shown in Fig. 4. The results of flexural strength show that all FCCs perform significantly better than PC at both dosages i.e. 0.5% and 1%. Peak load increases with the rising dosage of fiber for a given type of FCC. A maximum peak load or flexural strength is observed for FCCs incorporating HSF. FCC-HSF shows 25% and 47% higher flexural strength than PC at 0.5% and 1% volume of fiber, respectively. FCC-GF shows 15% and 28% higher flexural strength than PC at 0.5% and 1% fiber, respectively. FCC-PPF shows inferior performance compared to FCC-HSF and FCC-GF and it shows improvements of 9% and 18%, respectively at 0.5% and 1% fiber dosage. Higher elastic modulus and better bond strength of HSF compared to GF and PPF attributed to higher flexural strength of FCC-HSF [8,12]. GF has a high tensile strength but it shows poor bond strength with the binder matrix



(a)

(b)

(c)

Fig. 3. Load-deflection behavior of composites (a) FCC-HSF, (b) FCC-GF, and (c) FCC-PPF up to L/150 = 2 mm of deflection.

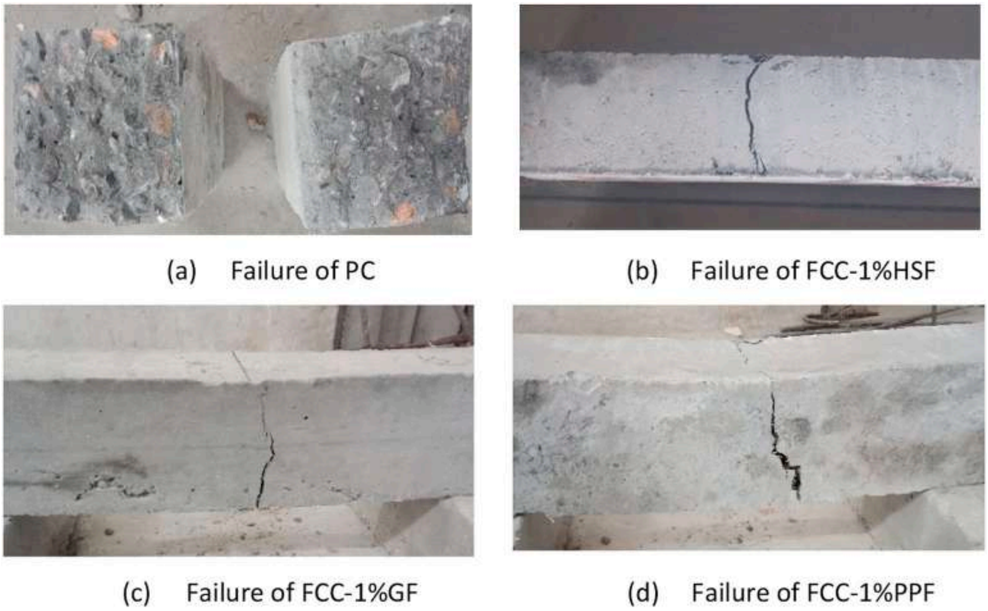


Fig. 5. Failure pattern of (a) PC (b) FCC-1%HSF (c) FCC-1%GF and (d) FCC-1%PPF after mid span deflection of 2 mm.

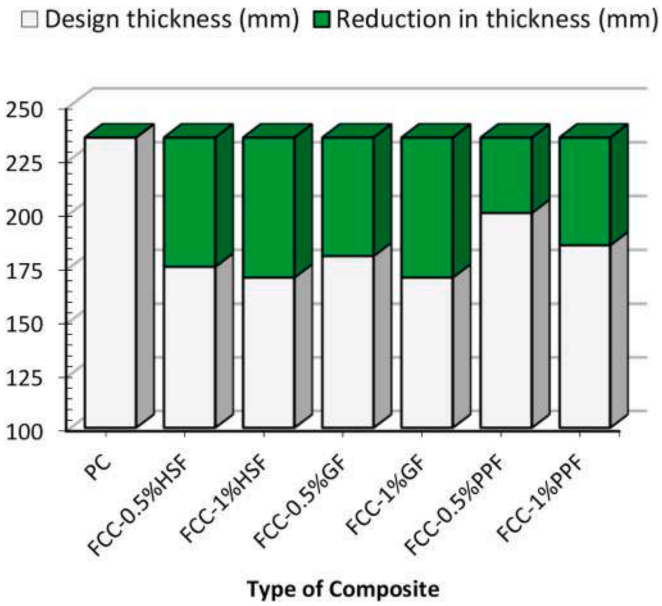


Fig. 6. Design thickness of jointed plain concrete pavement for each type of composites at similar load-carrying capacity.

[25]. The failure of HSF under tensile loading occurs due to rupture of fibers, whereas in the case of GF, fibers fail due to slippage; therefore, full efficiency of the tensile strength of GF cannot be utilized in resisting tensile stress. Furthermore, PPF has lower tensile strength and elastic modulus compared to both GF and HSF, which may be the reason for the inferior performance of FCC-PPF. The failure of PPF can occur due to both rupture (owing to its low tensile strength) and slippage of fibers (owing to its plain shape). Another interesting conclusion from the results is that FCC-HSF0.5 performs like both FCC-GF1 and FCC-PPF1. It means that a small fiber volume of HSF and a high fiber volume of PPF and GF yield similar benefits. This efficiency of HSF is already attributed to its better bond strength and higher elastic modulus compared to PPF and GF.

3.1.2. Residual strength

The residual strength evaluated from the load-deflection curves is shown for all mixes in Fig. 4. Overview of load-deflection data (see Fig. 3) shows that FCC-HSF has higher residual strength compared to FCCs with other fibers. High load intercept at 2 mm deflection (L/150 = 2 mm) is maximum for FCC-HSF at both dosages i.e. 0.5% and 1%. The residual strength of FCCs also depends upon the type of fiber. High bond strength of HSF can ensure better post-peak load-deflection behavior of concrete. Hooks of HSF provide better interlocking of fibers with the binder matrix than in the cases of plain fibers like GF and PPF. The plain fibers like GF and PPF may slip easily under very high tensile stresses (due to low pullout resistance compared to HSF) in the post-peak loads. Therefore, FCC-HSF shows higher residual strength than FCC-GF and FCC-PPF. PC does not reach the deflection of 2 mm because it fails suddenly after the peak load and it takes no considerable load after peak load. Therefore, the PC has zero residual strength. For a given fiber type, residual flexural strength increases with increasing fiber volume. This finding is in line with Xue et al. [6].

The failure pattern of PC, FCC-1%HSF, FCC-1%GF and FCC-1%PPF is shown in Fig. 5. It can be noticed that PC undergone a complete rupture prior to mid-span deflection of 2 mm. Whereas, FCC-1%HSF did not ruptured completely after 2 mm deflection retained sufficient strength after peak load compared to FCC-GF and FCC-PPF. Both FCC-GF and FCC-PPF did not show complete rupture like FCC-HSF after 2 mm deflection. But both FCC-GF and FCC-PPF retained smaller residual strength unlike FCC-HSF, and these mixes were more prone to rupture failure compared to FCC-HSF.

3.2. Design thickness of the pavement

Design thickness (h_{Design}) of pavement for each composite is shown in Fig. 6. It is noticed that h_{Design} reduces significantly with the addition of fiber in concrete. Fiber reinforcement can reduce the h_{Design} of pavement by 35–65 mm depending on the type and dosage of fiber. FCCs due to high flexural and residual strength yield smaller h_{Design} compared to PC for the same loadings on JPCP. Significance of role of fiber type and dosage is evident in h_{Design} reduction, for example, FCC-HSF yields a lower h_{Design} compared to FCC-GF and FCC-PPF. Moreover, FCC at 0.5% HSF yields lesser or comparable h_{Design} than FCCs containing 1% fiber volume of PPF or GF. This efficiency is ascribed to the high flexural strength of FCC-HSF compared to both GF and PPF-HSF at the same dose

Table 7
Cost per cubic meter of each composite (USD/m^3) (incl. 20 USD/m^3).

Mix IDs	Cement (USD/m^3)	Water (USD/m^3)	Coarse aggregate (USD/m^3)	Fine aggregate (USD/m^3)	SP (USD/m^3)	HSF (USD/m^3)	GF (USD/m^3)	PPF (USD/m^3)	Cost of Mix (USD/m^3)
PC	44.352	0.162	11.73	5.17	0.00	0	0	0	81.4
FCC-0.5% HSF	44.352	0.162	11.66	5.14	4.93	31	0	0	117.4
FCC-1% HSF	44.352	0.162	11.59	5.09	6.53	62	0	0	150.1
FCC-0.5% GF	44.352	0.162	11.66	5.14	4.93	0	9.75	0	96.0
FCC-1% GF	44.352	0.162	11.59	5.09	6.53	0	19.5	0	107.2
FCC-0.5% PPF	44.352	0.162	11.66	5.14	4.93	0	0	4.05	90.3
FCC-1% PPF	44.352	0.162	11.59	5.09	6.53	0	0	8.1	95.8

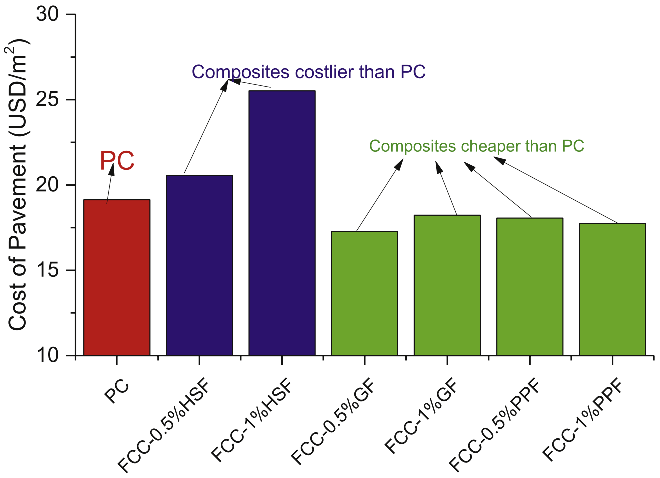


Fig. 7. Cost of pavement (CP) per square pavement for different concrete composites.

of fiber. No significant change in h_{Design} is noticed beyond 0.5% fiber volume in cases of both FCC-HSF and FCC-GF. This is because, at 0.5% fiber volume, h_{Design} of pavement with FCC-HSF and FCC-GF reaches very close to the minimum required thickness of 170 mm for a major arterial street (in any case h_{Design} should not be less than 170 mm [32]); therefore, when flexural strength is increased with the rise in fiber volume beyond 0.5%, no significant reduction is noticed in h_{Design} due to requirements of minimum possible thickness to avoid faulting. On the other hand, in the case of FCC-PPF, there is a substantial decrease in h_{Design} when PPF dosage is changed from 0.5% to 1%. It is because flexural strength of FCC-PPF at 0.5% fiber volume does not produce h_{Design} closer to the minimum required JPCP thickness. Furthermore, a small fiber volume of GF and HSF i.e. 0.5% yields smaller h_{Design} compared to a high fiber volume of PPF. This again shows that efficiency of PPF is lower than GF and HSF at the same fiber volume.

3.3. *Economic and environmental impact of pavement with different types of composites*

Costs of all concrete mixes are provided in Table 7. The cost of pavement (CP) per square meter with different types of composites is shown in Fig. 7. These results show that HSF is not an economical option as fiber to reduce the design thickness (h_{Design}) of pavement despite showing more efficiency in mechanical performance than other fibers i.e. GF and PPF. This is mainly because, for unit volume fractions, the mass of HSF (kg) is very high compared to both GF and PPF (see Table 7). For example, 0.5%HSF requires 39 kg of fiber, whereas, 0.5% GF and 0.5%PPF volume fractions require 13 kg and 4.5 kg of fiber, respectively. Therefore, HSF due to the requirement of a very high amount of mass per unit volume significantly increases the CP of the pavement. These results also show the importance of the strength per unit mass of fibers. Fiber like HSF, despite showing large reductions in the h_{Design} of pavement jeopardizes the economy of construction. Low-density fibers like GF and PPF, caused smaller reductions in the h_{Design} compared to that of the HSF, despite that CP of pavements with these fibers is significantly lower than that of the PC. This is only because of smaller increments in the cost of concrete mixes caused by PPF and GF (see Table 7). FCC-0.5%GF, FCC-1%GF, FCC-0.5%PPF and FCC-1%PPF can produce 10%, 5%, 6% and 8% cheaper pavements, respectively compared to conventional PC.

The calculation of carbon emissions per cubic meter of each mix is given in Table 8. Carbon emissions of pavement (CEP) per square meter (CO_2/m^2) with different mixes are given in Fig. 8. Overview of Table 8 indicates that all FCCs per unit volume production have a higher carbon footprint than that of PC. Moreover, HSF shows a higher carbon footprint than PPF, and GF mainly ascribed to two reasons (1) firstly because of the requirement of high mass per unit volume and (2) HSF also has a higher carbon footprint than both GF and PPF. Despite a high carbon footprint per cubic meter, the CEP of pavement with FCC is noticeably lower than that of the PC. This is because the FCC requires the lesser quantity of raw material (cement, coarse and fine aggregate) compared to PC in order to produce pavement for the same load-carrying capacity. Therefore, per square meter construction of pavement releases lesser emissions with FCC (except for FCC-HSF1) than the emissions released with PC. FCC-HSF1 shows a very huge CEP because of a drastic increase in CO_2 introduced by 1%HSF in the concrete mix, see Fig. 8. Moreover, FCC pavements with 0.5%HSF, 0.5%GF, 1%GF, 0.5%PPF and 1%PPF shows 4%, 18%, 17%, 13% and 18% lesser CEP compared to PC, respectively.

These results imply the usefulness of fiber-reinforcements to lessen the economic and environmental impacts of the pavement. Besides that, the use of conventional steel fiber is also being questioned in this research due to its very negative impact on the performance of pavements. The results are favoring the use of PPF and GF to reduce the environmental and economic impacts of pavement construction.

4. CONCLUSIONS

In this research, mechanical properties (flexural strength and residual strength) of different fibrous concrete composites (FCCs) (produced using hooked steel fibers (HSF), glass fibers (GF), and polypropylene

Table 8
Emissions (CO_2-kg) of each composite per cubic meter production.

Mix IDs	Cement (kg-CO_2/m^3)	Water (kg-CO_2/m^3)	Coarse aggregate (kg-CO_2/m^3)	Fine aggregate (kg-CO_2/m^3)	SP (kg-CO_2/m^3)	HSF (kg-CO_2/m^3)	GF (kg-CO_2/m^3)	PPF (kg-CO_2/m^3)	CO_2 of Mix (kg/m^3)
PC	303.6	0	30.7	1.19	0.000	0.00	0.00	0.00	355.5
FCC-0.5%HSF	303.6	0	30.5	1.19	0.006	103.35	0.00	0.00	458.6
FCC-1%HSF	303.6	0	30.3	1.17	0.008	206.70	0.00	0.00	561.8
FCC-0.5%GF	303.6	0	30.5	1.19	0.006	0.00	26.52	0.00	381.8
FCC-1%GF	303.6	0	30.3	1.17	0.008	0.00	53.04	0.00	408.1
FCC-0.5%PPF	303.6	0	30.5	1.19	0.006	0.00	0.00	8.33	363.6
FCC-1%PPF	303.6	0	30.3	1.17	0.008	0.00	0.00	16.65	371.7

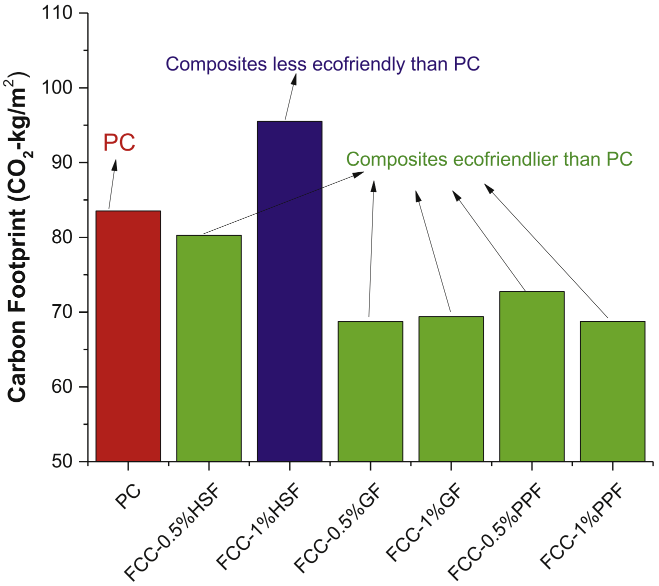


Fig. 8. Carbon emissions of pavement (CEP) per square of the meter with different concrete composites.

fibers (PPF)) were evaluated and used in the thickness design calculation of jointed plain concrete pavement (JPCP). Then, the cost of pavement (CP) and carbon emission of pavement (CEP) per square meter was analyzed for different FCCs. Following are important conclusions of this study:

1. At the same volume fraction, flexural strength and residual strength of HSF-FCC is higher than PPF and GF-FCC. 0.5% HSF produces improvements in flexural strength similar to 1%GF and 1%PPF.
2. The use of FCCs yields smaller design thicknesses (h_{Design}) compared to PC for the same load-carrying capacity. Moreover, no substantial reduction in h_{Design} is noticed when fiber volume of GF or HSF increases beyond 0.5%. For the given fiber volume, HSF yields smaller design thickness compared to GF and PPF.
3. Cost of pavement (CP) per unit area calculations show that HSF is not economical reinforcement compared to PPF and GF. FCC-0.5%GF, FCC-1%GF, FCC-0.5%PPF and FCC-1%PPF can produce 10%, 5%, 6% and 8% cheaper pavements, respectively compared to conventional PC.
4. FCC application can substantially reduce the carbon emissions of pavement (CEP) per unit area associated with materials production. Results favor composites incorporating GF and PPF for environmentally friendly pavements. FCC pavement with 0.5%HSF, 0.5% GF, 1%GF, 0.5%PPF and 1%PPF shows 4%, 18%, 17%, 13% and 18% lesser CEP compared to PC, respectively. However, FCC containing high fiber volume of HSF leads to high CEP compared to PC.

Recommendations

This research reveals the importance of fiber type and its dosage to achieve optimum mechanical, economic and environmental performance in pavement construction. Results of cost and carbon footprint analysis of pavements suggest that GF and PPF are more beneficial compared to HSF. Further research work is recommended on the analysis of cost and carbon footprint of pavement with ecofriendly fibers such as basalt fibers, recycled fibers, organic fibers, etc.

Credit author statement

Babar Ali: Methodology, Data Curation, Writing.
Liaqat Ali: Qureshi: Methodology, Conceptualization, Validation, Revising.
Rawaz Kurda: Validation, Revising.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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