Research Article

Development of Enhanced Polymer Fiber Reinforced Concrete

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Abstract: Polymers can contribute to the strength and flexibility of concrete formulations. A freshly assorted cement-based material is a particulate suspension far from its equilibrium state and possesses very non-linear and irreversible characteristics. The pavements made by bituminous and the requirement of continuous maintenance and even constructing it again guide us towards the cement concrete pavements. Cement concrete is advantageous over bituminous. It helps in investigating Polymer Fiber Reinforced Concrete (PFRC). PFRC enhances the reinforced concrete design, and it is proved as more durable than standard concrete pavements. The basic aim is to increase the compressive strength along with the tensile and flexural strength of PFRC. In particular, the highest compressive strength is observed between the low and high composition of fibers. At high weight fraction, the long fibers during mixing a formed pile of hair-like structure in concrete cylinder thus not helping the PFRC increase its strength. The utilization of fibers in cement can result in bond setting aside to 10 percent, and within sight of fly residue, saving might be up to 35 percent. All these benefits result in the overall enhanced durability of concrete.

Received: August 17, 2020; **Accepted:** June 22, 2021; **Published:** June 30, 2021
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Citation: Mushtaq, A., A. Nafees, R.M. Khan, A. Israr and Z.U. Ali. 2021. Development of enhanced polymer fiber reinforced concrete. *Journal of Engineering and Applied Sciences,* 40(1): 44-51.
DOI: https://dx.doi.org/10.17582/journal.jeas/40.1.44.51
Keywords: Concrete polymer, Fiber reinforced concrete, Cement concrete, Polymer fiber reinforced concrete, Nylon

Introduction

The better replacement to bitumen that is the bottom product of the distillation column is concrete. Recent advancements showed many alternates that can be used to improve the properties of pavement. Therefore, the perfect choice is the polymer fiber reinforced concrete pavements because it fulfills the requirement that is demanded in Pakistan for pavement material. A study from the literature explained that polymer fiber reinforcement concrete enhances durability and fuel efficiency. It was also stated that these concrete results in low maintenance cost, better riding quality, expanded load carrying capacity, and resistance to permeability of water over pliable pavements (Dhand *et al*., 2015; El-Messalami *et al*., 2021; Ganesh and Muthukannan, 2021). The concrete is formed by mixing sand and gravel or rocks with cement. It coats the surface and is hard with time which helps in binding the material together (Dhand *et al*., 2015).

Cement is replaced by polymer concrete as well as the polymer is added with the cement to form polymer cement concrete (PCC). The four different types of polymer concrete are: polymer cement concrete, polymer impregnated, polymer fiber reinforced and partially impregnated, and surface covered polymer concrete.

In recent past years, the development of FRC has been increased, but mostly steel fibers can be used as a reinforcement agent in concrete; steel fibers enhance the strength and increase the weight of concrete and course cost. To overcome this issue, we chose a polymeric fiber that is nylon as reinforcement in concrete. Added nylon fiber in different compositions and compared the strength of the PFRC samples with the normal concrete.

FRC pavements are extra durable than standard cement concrete pavement. The FRC is a composite material in which short length fibers are reinforced in concrete and uniformly dispersed. The fibers could be synthetic or natural materials (Kazusuke and Cho, 1986). FRC is viewed as a material with enhanced properties to provide concrete strength in the tension region. Fibers usually utilized in PFRC are steel fibers and polymeric fibers like nylon and polyester. This approach is environmentally good as most polymer waste could be reprocessed and utilized as reinforcement to concrete. Most of the waste polymers are non-biodegradable and cause environmental problems. Therefore, recycling these polymers helps in increasing strength and reduces environmental pollution; recycling those polymers make them efficient. Instead of disposing of it, we can use it efficiently and use its properties in pavement construction.

Concrete technology uses fibers to strengthen concrete structures; the major increase in compression strength has increased its importance worldwide. They use this technology and adapt it in different shapes, sizes, and colors for many building applications (Ohama, 2011; Sabnis, 2012). A feasibility study was conducted for recycling nylon fiber in concrete. Therefore, waste nylon fiber will be assured for recycling as long fibers to reduce the revised cost. Positive results can be expected if waste nylon is used as long fibers for concrete. Nylon fiber possesses outstanding physical properties, durability, mechanical and thermal properties. It is also very useful in engineering thermoplastic.

Materials and Methods

This study is based on enhanced polymer–fiber concrete and characterization of compressive, tensile, and flexural strength. It was using different proportions of nylon fibers mixing by different weight percent of concrete.

Selection of material for enhanced polymer fiber concrete

Raw materials used for the formation of samples are; Ordinary Portland Cement (OPC): Lucky Star, BS: EN 197-1:2000, strength class 42.N (50 kg net weight), fine aggregates: Sand, coarse aggregates: stones, water (tap water) and long polymer fibers (nylon). The addition of polymer improves the strength, durability, adhesion impermeability, and chemical resistance (Roudsari *et al.*, 2018). Incorporate polymer in concrete; the polymeric monomer is impregnated in concrete or mortar (Portland cement + water + sand aggregate) and then polymerized. PIC (polymer impregnated concrete) was obtained, which is superior in strength, chemical resistance and has less water absorption as compared to polymer-cement composites (Shanableh *et al.*, 2017). Polymer concrete is a type of composite where synthetic resins have replaced cement with a hardening agent and filler. The polymer concrete results in improved strength and properties of concrete. PPCC, in a fresh concrete mixture, either a monomer or polymer, is added, and polymerization is done if needed (Elsanadedy *et al.*, 2016). FRC is a composite where the binding agent is fibers which increases structural integrity. It contains fibers that are either short discrete, or randomly oriented. The properties of FRC vary with the type of fiber used, the geometry of fiber orientation, and densities (Kim and Bumadian, 2017).

A suitable mix design was used for the experiment, which was by weight percent 1:2:4 (cement: fine aggregate: coarse aggregate). The water to cement ratio varied with fiber content in samples. Sand, crushed stone, or gravel are considered aggregates. For a good concrete blend, aggregates must be spotless and solid particles are free of absorbed chemicals, clay coating, and other materials that might cause the worsening of concrete. The types of aggregates are coarse aggregate (>3/16 inch – 4.75 mm of No.4) and fine aggregate (<3/16 inch – >150 mm No. 200).

Development of enhanced polymer fiber concrete

The utilizing distinctive proportions of nylon fibers brought about an optimum fiber dosage of 0.15 % by weight of concrete. The properties of the nylon fibers are given in Table 1. The experimental concrete cylinders of size 4 by 8 inch and rectangular beams of 6 by 6 inch by 21 inches were cast both mixed with nylon fibers of optimum fiber diameter and water cured for 7 days. Cured specimens of the cylinder and rectangular beams were then tested for tensile, compressive, and flexural strength, respectively, and compared to specimens with no nylon fibers.

Table 1: *Properties of the nylon fibers.*

Properties	Test data
Diameter (D), mm	0.14
Melting point, K	324-463
Modulus, GPa	1.4-2.8
Specific gravity	1.15

The slump test is done to find the constancy of freshly made concrete. It is used as a path to review the correct proportion of water added to the mix. The test is completed by testing fresh concrete, BS EN 12350-2. It measures the workability of fresh concrete (Ashraful and Riyami, 2018). A concrete mixture by weight with appropriate water/ cement ratio is maked in the laboratory and requisite for casting six cubes after performing slump test (Chin *et al*., 2018). Figure 1a shows the procedure for sampling the slump test. A solid blend by the load with appropriate water/ concrete proportion is set up in the research center and required for throwing six 3D squares in the wake of directing slump test.

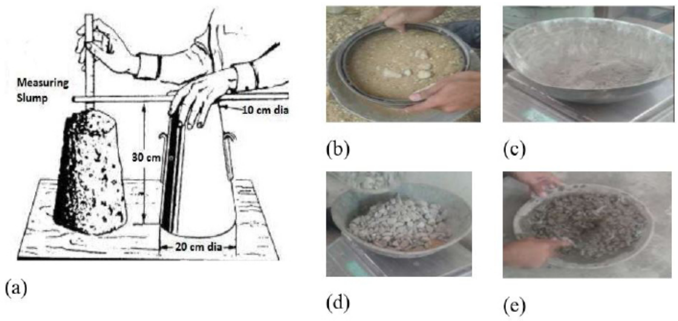

Figure 1: *Sampling and mixture design (a) Slump test; (b) Fine aggregates of sand; (c) Portland cement; (d) Coarse aggregate (e) Mixed proportion.*

Mix design of 1:2:4 (cement: fine aggregate: coarse aggregate) was used for this experiment as shown in Figure 1b, c, d and e. The water to cement ratio was 0.6, and fiber content was varied, which is used in the sample; the approximate total weight of the cylinder and the rectangular beam was 4200 g and 12000g, respectively. Sieving is a procedure to measure the particle size distribution of material. They were using the sieves of a required number having meshes according to the size of the particle. The arrangement of sieves was so that a large particle size sieve at the top and then in descending order. For coarse aggregates, ½ inch linear (50% of aggregate), 3/8 inch linear (50% aggregate), and sieve number 4 were used. For fine aggregate sieve number 50, 30 and 4 was used. The pass of sieve number 4 was rejected (Ferreira and Diniz, 2017; Kazusuke and Cho, 1986). The dry materials were first mixed, and then after the addition of water, the mixture was thoroughly mixed and molded (Babatunde, 2017).

The fibers were mixed by hand mixer for these experiments, and for large quantities of material, the rotary drum can also be used. The sand, cement, and aggregates were first mixed separately in a mixing tray. Then fibers were added uniformly and again mixed thoroughly. Water is then added and mixed with the rest of the material. This mixture is then inserted into moulds. The following steps are taken; the first screw was tightened to tight the mould, then oiled the mould so that the concrete mixture will not stick to that surface of the mould. At that point, the mould was tamped with fresh concrete in three steps each time it is filled by a rod of standard dimension. Later the surface of the mould must be planned. After 24 hours, the mould was de-moulded, and the concrete block was put into the water pool for curing.

Curing is very important, and it helps in the development of strength and durability. It is done after the mixing of concrete. Moisture is to be taken care of should be maintained the temperature conditions both at depth and close the surface for a prolonged period appropriately. Cured concrete has a suitable amount of moisture content for hydration and improvement of abrasion, strength, scaling resistance, volume stability, and resistance to freezing (Babatunde, 2017; Elsanadedy *et al*., 2016). The precast concrete specimens are immersed in a curing tank underwater for seven days. After seven days, the specimen was dried under normal weather conditions, and after that, the specimen was tested for compression, tensile and flexural testing. The cured samples were then put through testing of respective testing equipment for desired testing (Kazusuke and Cho, 1986; Kim and Bumadian, 2017).

Characterization of enhanced polymer fiber concrete

Figure 2 a demonstrates the concrete cylinder during compressive testing. Cylinders must be engaged in the compression testing machine and loaded to complete failure. The loading rate on a hydraulic machine ought to be kept up in 20-50 psi/s (0.15 - 0.35 MPa/s) amid the last 50 % of the loading phase.

The sort of break ought to be recorded. The concrete strength is determined by dividing the most extreme load at failure by the average cross-sectional range. As a minimum, two cylinders are tested at a comparable age, and the average strength is represented as the test result to the closest 10 psi (0.1 MPa).

$$\textit{Compressive strength} = \frac{F}{A} \ldots (1)$$

Where, F = maximum load at failure, A = cross-sectional area, force taken at failure = 189.86 kN and radius = 2 inch = 0.0508 m. Therefore; A = 0.0081m^2 and compressive strength = 23.4 MPa.

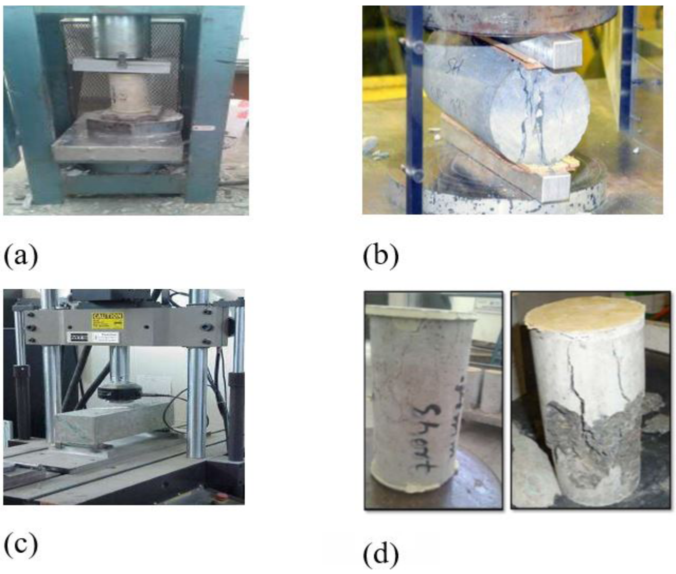

Figure 2: *Concrete testing (a) Compressive cylinder; (b) Split tensile cylinder; (c) Rectangular beam; (d) Comparison between PFRC and non-PFRC.*

The tensile strength of concrete determines the splitting tensile strength test utilized on the concrete cylinder. Figure 2b portraits the equipment used as are compression testing machine and metal plates (30 cm long and 4 cm thick). Draw diametrical lines at the closures of the sample to guarantee that they are in a similar axial place. Record the sample's dimension, and weight then set the compression testing machine for the required range. Regulate the sample so that the lines on the terminations are vertical and centered over the base plate. Spot the other metal strip over the sample. Cut down the upper plate to contact the metal strip. Put on the load reliably without daze at a rate of around 14-21 kg/cm^2/minute (compares to a total load of 9900 kg/minute to 14850 kg/minute) record the breaking load (F).

$$\textit{Tensile Strength} = \frac{2F}{\pi DL} \ldots (2)$$

Where, F = maximum applied load at failure, D = Diameter of cylinder, and L = Length of cylinder, force taken at failure = 80kN, diameter = 4inch = 0.1016m and length = 8 inch = 0.2032m. Therefore; tensile strength = 2.4 MPa.

Flexural strength is one proportion of the tensile strength of concrete. It is estimated of a concrete beam or unreinforced slab to oppose failure during mixing. It is calculated by loading 6 x 6-inch concrete beams with a range length at least multiple times the depth. The flexural quality is granted as modulus of rupture (M.R.) in psi (MPa) and is overseen by standard test procedures ASTM C 78 (third-point stacking) or ASTM C 293 (focus point stacking). In the f1exural quality testing system, a nominal 6 by 6 inch by 21 inch (152.4 by 152.4 by 530 mm) solid beam is appeared in Figure 2c. Place sample on its side, centered in the machine, to the point that at least 1 in (25 mm) of the pillar reaches out outside the help rollers. Apply a heap somewhere in the range of 3 and 6% of the normal extreme load.

The heap might be applied quickly until roughly half of the breaking load has come. Past that point, lessen the loading rate, so the increment rate in extraordinary fiber stress stays inside 125 to 175 psi (861 to 1207 kPa) per minute until the point when the specimen breaks (1500 to 2100 lb$_f$ every moment). Take and record three estimations at the break over each measurement (one at each edge and the middle) to the closest 0.05 in (1.3 mm) to determine the average depth, width line of fracture area of the specimen at the segment of failure.

$$\textit{Flexural Strength}\ (R) = \frac{3PL}{2bd^2} \ldots (3)$$

Where; R is the modulus of rupture, P represents maximum load, L is the span length, b is average width, and d denotes average depth. The span length = 18 inch = 0.457 m, load at failure = 9.09 kN, width and depth = 6 inch = 0.1542 m and

$$\textit{Flexural Strength}\ (R) = 1.76 \text{ MPa.}$$

Results and Discussion

The samples were tested for compressive, tensile, and flexural strength. The average results of these samples were determined. The increase in properties has been observed when the fiber content was increased up to 0.15%. At 0.2%, properties decreased because high fiber content created a problem of bonding between matrix and reinforcement.

Compressive strength

PFRC cylindrical specimens of 4 x 8-inch size were cast. The PFRC cylindrical specimens were cured for seven days, and their compressive strength is measured at the different compositions of fiber loading, as shown in Figure 3. A consistent property was observed at fiber loading of 0.15%, where compressive strength was 23 MPa, indicating that is no decrease in compressive strength of FRC with the same composition (Parvin and Raad, 2018). Figure 2d shows the comparison of test samples between PFRC and Non-PFRC cylinders after the compressive test.

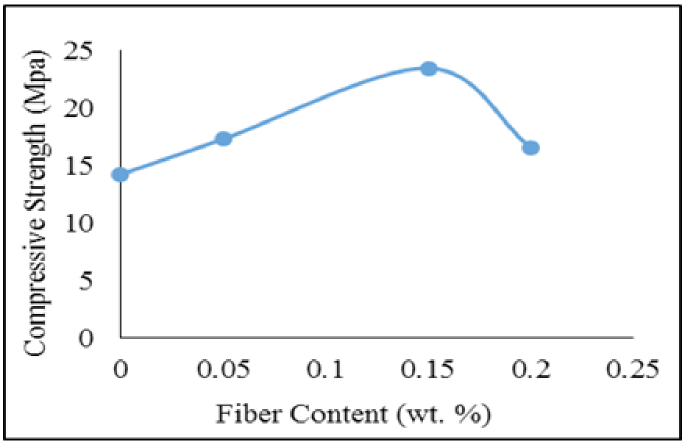

Figure 3: *Compressive strength comparison between the Non-PFRC and PFRC different compositions of fiber.*

From Figure 3, the variation in compressive strength between the non-PFRC and PFRC of different fiber compositions. These differences can be because of the hydrophilic nature of nylon fibers that did not allow fibers to slip out during wet curing (Kanalli *et al.*, 2014). At a lower composition of nylon fiber, the compressive strength is not impressive; a similar case is being observed at the higher composition of nylon fibers. The roughness of the concrete surface helps the fibers to impregnate with high interfacial bond strength between concrete and fibers (Khandelwal and Rhee, 2020; Melcer *et al.*, 2017). In particular, the highest compressive strength is observed between the low and high composition of fibers, at 0.15 wt. % of concrete, it could be because, at low fiber content, the composition of fibers was not enough to provide high strength. In contrast, in high composition, the weight fraction of fiber was high that they accumulate a high volume fraction reducing the binding strength of concrete itself (Arunothayan *et al.*, 2020; Chu *et al.*, 2021).

Tensile strength result

PFRC cylindrical specimens of 4 by 8-inch size were cast. The PFRC cylindrical specimens yielded maximum tensile strength of 4.9 MPa when tested at seven days. Figure 4 shows the variation in tensile strengths between the non-PFRC and PFRC of different compositions, and the length of fiber can be observed. It can be attributed to the hydrophilic nature of nylon fibers did not allow fibers to slip out during wet curing. At long fiber length, the tensile strength of concrete decreases at 0.20 wt. % from the normal concrete. It could be because as the force was applied to the cylinder, the long fibers are easily slipped out in the tensile test. Thus, fibers accumulating volume in the concrete cylinder but failing to increase the cylinder's tensile strength resulting in an overall drop in tensile strength of the PFRC cylinder. At a lower composition of nylon fiber, the tensile strength is not impressive; a similar case is observed at the higher composition of nylon fibers. The roughness of the concrete surface helps the fibers to impregnate with high interfacial bond strength between concrete and fibers (Ahmed and Ali, 2020; Shanableh *et al.*, 2017).

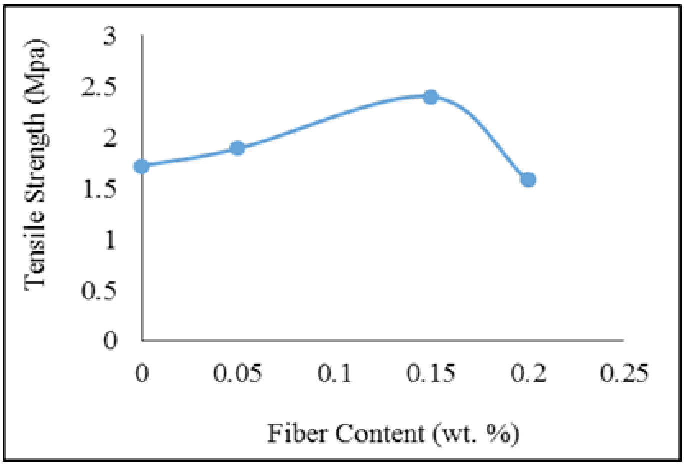

Figure 4: *Tensile strength comparison between the Non-PFRC and PFRC different compositions of fiber.*

At high weight fraction, the long fibers during mixing a formed pile of hair-like structure in concrete cylinder thus not helping the PFRC increase its strength. In particular, the highest tensile strength is observed between the low and high composition of fibers at 0.15 wt %.

Flexural strength result

PFRC rectangular beam specimens of 6 by 6 by 21-

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inch size were cast. A center point loading test tested the beams for flexural strength. The PFRC beam specimens yielded maximum flexural strength of 1.76 MPa when tested at seven days.

Figure 5 represents the variation in flexural strengths between the non-PFRC and PFRC of different compositions can be observed some difference because the hydrophilic nature of nylon fibers helps fiber not to slip out during wet curing (Ashraful and Riyami, 2018; Hawileh *et al*., 2014). At long fiber length, the flexural strength of the concrete beam decreases at 0.20 wt. % from the normal concrete beam. Thus, fibers accumulating volume in the concrete beam but failing to increase the beam's flexural strength resulting in an overall drop in flexural strength of the PFRC beam. The roughness of the concrete surface helps the fibers to impregnate with high interfacial bond strength between concrete and fibers (Chin *et al*., 2018). At high weight fraction 0.20 wt. % of the long fibers, the fibers during mixing a formed pile of hair-like structure in concrete thus not helping the PFRC beam increase its strength. In particular, the highest flexural strength is being observed at 0.15 wt. % of concrete and as the fiber content increases, the flexural strength started to decrease as they accumulate high volume fraction and are not uniformly mixed, thus decreasing the binding capability of concrete (Dhand *et al*., 2015; El-Messalami *et al*., 2021; Ganesh and Muthukannan, 2021).

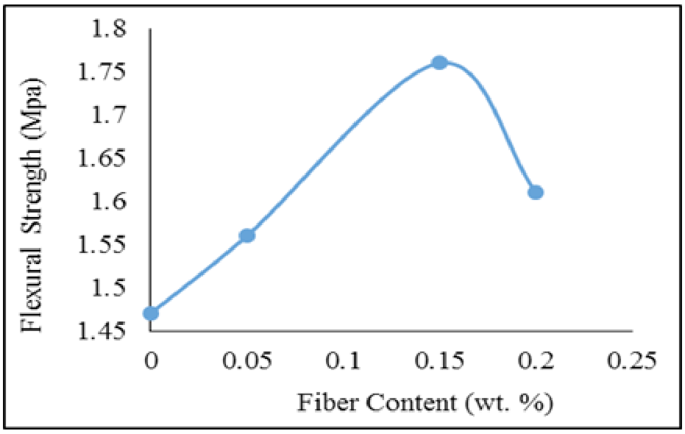

Figure 5: *Flexural strength comparison between the Non-PFRC and PFRC different compositions of fiber.*

Waterlogging is a noteworthy purpose behind potholes in roads. The asphalt roads are penetrable to water that destructions the road and sub-level. Be that as it may, PFRC streets are exceptionally impermeable to water so that they won't permit waterlogging, and water is turning out at first glance from the sub-level. Usage of sensors on streets will be simpler while utilizing polymer strands for concrete. Maintenance actions identified with steel consumption will be decreased while utilizing PFRC. In crisp solid polymer, filaments diminish the settlement of total particles from the asphalt surface, bringing about an impermeable and more resilient, slip-safe asphalt (Pham and Hao, 2016; Sabnis, 2012). Fibers decrease plastic shrinkage and cracking. It also affords residual strength; subsequently, cracking happened. The utilization of PFRC produces cement of enhanced abrasion and impact resistance. PFRC additionally improves the ductile and flexural durability of cement (Huo *et al*., 2018; Parvin and Raad, 2018). The utilization of fibers in cement can result in bond setting aside to 10% and within sight of fly residue, saving up to 35%. All these benefits result in the overall enhanced durability of concrete. The hindrance is that the utilization of PFRC, being a general innovation, represents a risk of a high introductory cost of development.

Conclusions and Recommendations

Polymer fiber reinforced concrete (PFRC) can be used vigorously in place of normal concrete pavement. Polymeric fibers, nylon was used due to corrosion resistance and low cost. Polymer fiber reinforced concrete needs specific design considerations with creative processes to obtain optimal performance. The high cost is balanced by the reduction in maintenance and restoration operations, make polymer fiber reinforced concrete cheaper than flexible pavement. This study showed that balanced properties of concrete had been achieved when the fiber is used at 0.15 wt %. The properties were decreased above and below 0.15% fiber loading because of agglomerates and fiber bonding issues. In vast and fast-developing countries, road networks ensure mobility of resources and contribute to advance development. Enhanced properties of polymer fiber reinforced concrete through polymer fibers ensure that it can be easily used in concrete to increase the main properties of concrete, like compressive strength and tensile strength. Polymer fiber reinforced concrete opens new courage to emerging and globalizing the quality.

Acknowledgements

The authors would like to acknowledge the Department of Polymer and Petrochemical Engineering, NED

University of Engineering and Technology, Karachi, Pakistan, for supporting this research work.

Novelty Statement

In this research project, developed Polymer Fiber Reinforced Concrete (PFRC) enhances the reinforced concrete design, and it is more durable than standard concrete pavements.

Author's Contribution

Asim Mushtaq: Conceptualization, development, analysis and paper writing.
Asra Nafees: Supervision, provided guidelines and delivered resources.
Raza Muhammad Khan: Provide technical concept and collected the data.
Amina Israr: Perform the experimental work and analysis.
Zaeem Uddin Ali: Calibration of the equipment and guidelines about the equipments.

Conflict of interest
The authors have declared no conflict of interest.

References

Ahmed, S., and M. Ali. 2020. Use of agriculture waste as short discrete fibers and glass-fiber-reinforced-polymer rebars in concrete walls for enhancing impact resistance. J. Cleaner Prod., 268(1): 1-18. https://doi.org/10.1016/j.jclepro.2020.122211

Arunothayan, A.R., B. Nematollahi, R. Ranade, S.H. Bong and J. Sanjayan. 2020. Development of 3D-printable ultra-high performance fiber-reinforced concrete for digital construction. Const. Build. Mater., 257(1): 1-11. https://doi.org/10.1016/j.conbuildmat.2020.119546

Ashraful, A.M., and K.A. Riyami. 2018. Shear strengthening of reinforced concrete beams with external steel bars and with CRFP. Const. Build. Mater., 162: 683-696. https://doi.org/10.1016/j.conbuildmat.2017.12.011

Babatunde, S.A., 2017. Review of strengthening techniques for masonry using fiber reinforced polymers. Composite Struct., 161: 246-255. https://doi.org/10.1016/j.compstruct.2016.10.132

Chin, S.C., F.S. Tong, S.I. Doh, J. Gimbun, Y.K. Foo and J.P. Siregar. 2018. Potential external strengthening of reinforced concrete beam using natural fiber composite plate. Appl. Mech. Mater., 878: 41-48. https://doi.org/10.4028/www.scientific.net/AMM.878.41

Chu, S.H., L.G. Li and A.K.H. Kwan. 2021. Development of extrudable high strength fiber reinforced concrete incorporating nano calcium carbonate. Addit. Manufact., 37(1): 1-9. https://doi.org/10.1016/j.addma.2020.101617

Dhand, V., G. Mittal, K.Y. Rhee, S.J. Park and D. Hui. 2015. A short review on basalt fiber reinforced polymer composites. Composit. B Eng., 73: 166-180. https://doi.org/10.1016/j.compositesb.2014.12.011

El-Messalami, N., F. Abed and A. El-Refai. 2021. Response of concrete columns reinforced with longitudinal and transverse BFRP bars under concentric and eccentric loading. Composit. Struct., 255 (1): 1-12. https://doi.org/10.1016/j.compstruct.2020.113057

Elsanadedy, H., T. Almusallam, Y. Al-Salloum and R. Iqbal. 2016. Effect of high temperature on structural response of reinforced concrete circular columns strengthened with fiber reinforced polymer composites. J. Composit. Mater., 51(3): 333-355. https://doi.org/10.1177/0021998316645171

Ferreira, J.R., and S.M.C. Diniz. 2017. Model uncertainty in the estimation of the resistance of circular reinforced concrete columns confined by carbon fiber reinforced polymer. Struct. Inf. Eng., 14(1): 68-88. https://doi.org/10.1080/15732479.2017.1328447

Ganesh, A.C., and M. Muthukannan. 2021. Development of high performance sustainable optimized fiber reinforced geopolymer concrete and prediction of compressive strength. J. Clean. Prod., 282(1): 1-13. https://doi.org/10.1016/j.jclepro.2020.124543

Hawileh, R.A., H.A. Rasheed, J.A. Abdalla and A.K. Al-Tamimi. 2014. Behavior of reinforced concrete beams strengthened with externally bonded hybrid fiber reinforced polymer systems. Mater. Design, 53: 972-982. https://doi.org/10.1016/j.matdes.2013.07.087

Huo, J., Z. Li, L. Zhao, J. Liu and Y. Xiao. 2018. Dynamic behavior of carbon fiber-reinforced polymer strengthened reinforced concrete beams without stirrups under impact loading. Struct. J., 115(3): 775-787. https://doi.

org/10.14359/51701283

Kanalli, S.A., R. Palankar, B. Kumar, P. Kumar and Prakash S.K., 2014. Comparative study of polymer fibre reinforced concrete with conventional concrete pavement. Int. J. Res. Eng. Technol., 3(1): 139-143. https://doi.org/10.15623/ijret.2014.0301022

Kazusuke, K., and R. Cho. 1986. U.S. Patent 4,565,840 Patent No.

Khandelwal, S., and K.Y. Rhee. 2020. Recent advances in basalt-fiber-reinforced composites: Tailoring the fiber-matrix interface. Composit. B Eng., 192(2): 1-13. https://doi.org/10.1016/j.compositesb.2020.108011

Kim, Y.J., and I. Bumadian. 2017. Chemicoelectrical response of concrete bonded with carbon fiber-reinforced polymer sheets in a corrosive environment. ACI Mater. J., 114(4): 549-558. https://doi.org/10.14359/51689713

Melcer, J., M. Žmindák, P. Novák, V. Dekýš and K. Kotrasova. 2017. Analysis of bond behaviour in strengthened reinforced concrete beam with carbon fiber reinforced polymer lamella. MATEC Web Conf., 107: 45-50. https://doi.org/10.1051/matecconf/201710700045

Ohama, Y., 2011. Concrete-polymer composites, the past, present and future. Key Eng. Mater., 466: 1-14. https://doi.org/10.4028/www.scientific.net/KEM.466.1

Parvin, A., and J. Raad. 2018. Internal and external reinforcement of concrete members by use of shape memory alloy and fiber reinforced polymers under cyclic loading. A review. Polymers, 10(4): 376. https://doi.org/10.3390/polym10040376

Pham, T.M., and H. Hao. 2016. Behavior of fiber-reinforced polymer-strengthened reinforced concrete beams under static and impact loads. Int. J. Prot. Struc, 8(1): 3-24. https://doi.org/10.1177/2041419616658730

Roudsari, S., S. Hamoush, S. Soleimani, T. Abu-Lebdeh and M. HaghighiFar. 2018. Analytical study of reinforced concrete beams strengthened by FRP bars subjected to impact loading conditions. Am. J. Eng. Appl. Sci., pp. 1-19. https://doi.org/10.3844/ajeassp.2018.407.425

Sabnis, G.M., 2012. Green building with concrete: Sustainable design and construction Green building with concrete: sustainable design and construction. U.S: CRC Press. https://doi.org/10.1201/b11376

Shanableh, A., Karzad, A.S., Al-Toubat, S., Maalej M. and Estephane, P., 2017. Repair of reinforced concrete beams using carbon fiber reinforced polymer. MATEC Web of Conf., 120: 1-8. https://doi.org/10.1051/matecconf/201712000001