Effectiveness of Hybrid Fibers in Cementitious Composites Towards Sustainability: A Review

Ali Rehman
Department of civil engineering
Capital university of science and technology
Islamabad, Pakistan
engr.dr.alirehman@outlook.com

Majid Ali
Department of civil engineering
Capital university of science and technology
Islamabad, Pakistan
majid.ali@cust.edu.pk

Abstract

Cementitious composites with less effect on the environment and lower cost are the major components for advanced technology of interest. For concrete composites a lot of negative effects on environment were observed because of the emission of greenhouse gases, deficiency in materials availability, and higher consumption of energy. Hybrid fiber reinforced concrete which is the mixture of different types of fibers in cementitious composites with an enhanced behavior in mechanical properties of cement-based composites as compared to that of single fiber reinforced composites. The incorporation of natural fibers in cementitious composites have relative effects on environment which is one of the major aspects related to sustainability. The overall aim of this research is to explore the behavior of hybrid fiber cement composites towards sustainability and to promote the use of hybrid fibers in composites for improved mechanical properties. The current research is the review of previous studies related to utilization of hybrid fibers in cement composites considering sustainability aspect. In this paper, a review has been done. The purpose of this research is to explore the use of natural fibers hybridization with artificial fibers in cementitious composites for sustainable construction. This paper will provide a brief summary about the benefits of using natural hybrid fibers for sustainable construction. Also, it will promote the potential use of hybrid fibers in cementitious composites. Moreover, the benefits of fiber inclusion in cement composites like enhancement in the mechanical properties of hybrid fibers cementitious composites have increase the demand of these type of composites with introducing the novel principles taking into consideration for sustainability. Thus, addition of natural fibers with artificial/synthetic fibers can be another step toward the sustainability in the concrete industry. This research outcomes would present a valuable reference for both practitioners of industry and research of academia that are interested in the development of sustainable construction materials.

Keywords: Hybrid fiber reinforced concrete, natural fiber, synthetic fiber, mechanical properties, sustainability

IEECP'21, July 29-30, 2021, Silicon Valley, San Francisco, CA – USA

***DAI :** https://sci-index.com/DAI/2021.99101/IEECP/14899341*

I. INTRODUCTION

The incorporation of fibers helps the cement based composites to overcome its weaknesses like less tension, higher shrinkage and lower resistance against impact loading [1]. Few of the natural fibers that are utilized in the productions of cement concrete are jute fiber, sisal fiber, hemp fiber, coir fiber, flax fiber and cotton fiber [2, 3]. Worldwide, the local availability of these natural fibers results in no fiber scarceness and available at a low cost. Usually the natural fibers are environmental friendly and nonabrasive material [4]. The natural fiber cement composites have shown favorable properties by using few structural materials, which offers the best application for nanotechnology [5-7]. Numerous natural and artificial fibers (i.e., glass, steel, and synthetic) are available commercially [8-10]. Among the fibers, polypropylene fiber and glass fiber are two excellent micro-reinforcing materials to increase cement concrete's strength properties. Investigations about adding polypropylene fiber and glass in the cement concrete composite have been carried out to improve its mechanical properties. The addition of polypropylene fiber or glass fiber can bridge micro-cracks in the mixture and re-divided stress, and stop stress from growing at the crack location. [11, 12]. Various kinds of fibers like polypropylene fibers, steel fibers, nylon fibers, basalt fibers, and glass fibers are used to produce fiber reinforced concrete. Polypropylene fibers have been an interest of researchers because of their resistivity to shrinkage, higher roughness, and cheap cost [13].

The utilization of fiber in cement composites impacts the environment and industrial pollution; that's why there is an increment in the demand of fiber nowadays. Novel natural materials are used in conventional cement concrete composites to minimize the negative environmental impact [14-16]. The addition of macro synthetic fiber reinforced concrete expanded fast over the past two decades. It was concluded that macro synthetic fiber has better benefits as equated to steel fiber, cheaply available, easily mixed with cement concrete, weight lightness, less corrosive in cement concrete, and give resistance against destructive chemicals [17, 18]. The incorporation of hybrid basalt polypropylene fibers in cement composites is going towards popularity recently. Basalt fiber give superior physical and mechanical properties, stability of higher temperature, excellent tensile strength, incredible resistance to acid alkali, and a strong capacity for plastic deformation, which is a novel variety of environment-friendly, low cost, and green fiber [19, 20]. The addition of recycled aggregates in structural cement concrete composites is a step towards a sustainable solution to minimize the misuse of natural sources and the adverse ecological impacts of cement concrete waste [21]. Investigators are now exploring the use of recycled materials from damaged vehicle tires, for example, crumb rubber aggregate in cement concrete composites, to overcome the problems generated by waste tires and protect the environment by creating it green and sustainable [22]. Additionally, the investigation stated that the performance of natural coconut fiber and rope with cement concrete reinforced beam under dynamic loading was improved [23]. Moreover, research was conducted on coconut fiber reinforced concrete and coconut fiber ropes utilization to determine the behavior for seismic-resistant construction [24]. The seismic behavior of coconut fiber reinforced concrete columns with various reinforcing arrangements of coconut fiber ropes were studied. This is an innovative material, which is under exploration for the making of safe shelters with cheaper cost in the regions where earthquakes occur [25]. Another research was carried out on the determination of post-tensioned coconut fiber ropes to control uplifts of interlocking blocks for mortar-free construction throughout seismic loadings [26].

The significance of the present research is to review the behavior of hybrid fiber reinforced concrete in the light of sustainability. In this study, different hybridization of artificial and natural fibers together is reviewed for the mechanical properties of cement composites. In addition, the effect of hybrid fibers reinforced concrete on environment is also studied. In this paper, a review has been done. The purpose of this research is to explore the use of natural fibers hybridization with artificial fibers in cementitious composites for sustainable construction. This paper will provide a brief summary about the benefits of using natural hybrid fibers for sustainable construction. Also, it will promote the potential use of hybrid fibers in cementitious composites.

II. CONCEPT OF HYBRID FIBERS

In the concrete industry, hybrid fiber reinforced concrete has been of great importance. When the combination of two or more fibers are used in cement concrete composites, then, as a result, a hybrid fiber reinforced concrete is obtained. Each fiber that is used in hybrid fiber-reinforced cement concrete shows their promising effects on composites [23]. The system of fiber hybridization needs a mixture of various kinds of fibers to produce a synergic impact and improve the cement composite behavior for properties of the fresh state and hardened state [24]. Steel with polypropylene hybridization has been getting popularity amongst different hybrid fiber reinforced combinations. Although concrete develops shrinkage and internal stresses, the hybrid steel polypropylene fiber reinforced cement composites have the ability to divide stresses in every direction over millions of polypropylene fibers available in the mixture [25]. On the other hand, the benefit of utilizing a hybrid fiber in concrete is that it minimizes the structure's dead load because of the low density of the polypropylene fibers as compared to that of steel fibers.

III. BEHAVIOUR OF HYBRID FIBER REINFORCED COMPOSITES

Synthetic fibers, like polypropylene fibers, have recently attracted a lot of attention. For the better mechanical properties of cement concrete reinforced with various kinds of hybrid fibers, the mono-fiber is generally preferred to cement concrete reinforcement. It is strongly recognized that thick and longer fibers restrict the spreading of macro cracks and increase the toughness at the region of post cracking [27]. Whereas micro and shorter fibers bridge the micro cracks, which results in improving the peak strength of composites [28]. Accordingly, the investigators usually select the mixture of fibers with various lengths, diameters, and elastic modulus [29], [19]. Moreover, fiber reinforced cement concrete composites also provide significant obstruction to the development and spreading of cracks [30]. After a detailed study, it is summarized that polypropylene fiber and steel fiber are used frequently in composites. A vital role was played by the aspect ratio and content of fibers in composites for enhancing multiple properties of cement composites. Fibers start sustaining the load during the occurrence of cracks. The fibers start transferring more stresses to the composites while increasing the load on specimens. Fiber fracture or pull-out of the fiber was observed during these stresses that pass the bond strength among the matrix and the fiber [31]. Compared to ordinary and single-length fiber reinforced mortar, the combination of basalt fiber with four various lengths incorporating in cementitious based composites enhanced mechanical performance [32]. In order to get superior structural strength, it is essential to include fibers in ordinary cement mortar [33]. Due to its bridging action, the incorporation of recycled nylon fibers in cement mortar reduces the number and width of cracks [34, 35].

Figure 2 represents a schematic diagram to demonstrate fiber's primary bridging mechanism for cement concrete reinforced with hybrid polypropylene and steel fibers under flexure loading. Many internal macro or micro-cracks develop at the start of loading because of the inherent shortcomings and composites shrinkage; meanwhile, the major surface crack has not appeared. Although, individually dispersed fibers could bridge the cracks, reducing the stress from the composites. So, the polypropylene fiber has the ability to counter the small micro-cracks propagation due to its weak bond with the mixture and more vulnerable tensile properties (i.e., the pull-out load is very low). While the loading raises, the major crack gradually produces, and the fiber tie together presents a crucial act in enhancing the flexure behavior. The slippage of fiber and less bonding can take place, whereas low interaction among mixture and fiber. And probably increase at the interface of polypropylene fiber and the mix. Fiber fracture occurs when the concentrated stress reduces the fiber reinforcement boundary; however, the fiber has completely adhered to the mixture; it was also noticed at the interface of recycled tire steel fiber and the mix. Both phenomenon's showed enrichment of post-cracking achievement, particularly energy absorption capacity, so as the value of energy absorption is altered by multiple factors like the number of fiber and the spacing of fibers nearby a specific crack [36].

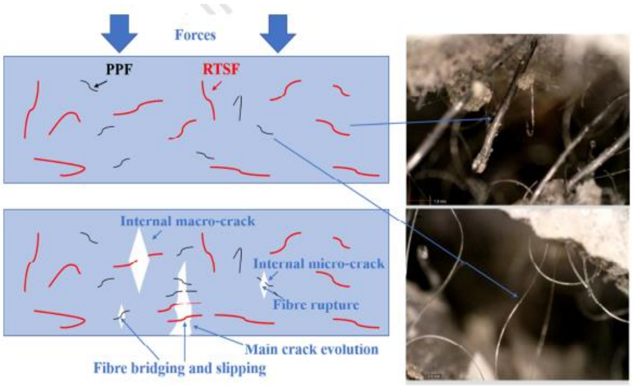

Figure 1. Hybrid fiber reinforced concrete bridging mechanism under flexural loading [36].

IV. HYBRIDIZATION WITH ARTIFICIAL AND NATURAL FIBERS

Experimental research has been taken to assess the enhancement in mechanical properties of interlocked masonry walling without mortar by incorporating natural fibers such as sisal fibers and rice straw used in the mixture of plaster. The terminology for increment in failure loads across non-plastered columns was noticed up to 5 times for control mix and up to 21 times for plaster mix with fibers [37]. Further experimental research was conducted to evaluate shear strengths, and residual compressive strengths for new coconut fiber reinforced concrete interlocking blocks. After sustaining a set of dynamic loading, the increment up to 3.2% and 5.7% for in-plane strength and compressive strength was observed. This enhancement represents the merits of earthquake loading on structures without mortar [38]. Another study was carried out on the addition of natural plant fibers, i.e., wheat straw, to increase the performance and potential of reinforced concrete for structural applications. Experimental results revealed an improvement of 7.5% for flexure strength, 30.4% for energy absorption, 11.1% for toughness indices, and a good crack arresting mechanism by utilizing wheat straw in fiber reinforced concrete. Moreover, rigid concrete pavement having wheat straw has an equivalent design with a seeming more sustainable and more long-lasting structure [39]. The performance of jute fiber reinforced concrete composites is explored practically under impact and dynamic loading conditions. The resistivity against impact loading by the jute fiber reinforced concrete composites is improved up to 6 times compared with normal concrete. The 100% damping ratio and 68% dynamic young's modulus were also improved. The improvement in splitting tensile strength was 8%, while the flexure strength was 20% observed. According to the results, short jute fibers in cement concrete composites may minimize steel reinforcement of slabs by roughly 28% [40]. Furthermore, the reinforcing index and constitutive modeling are explored for normal concrete, single fiber reinforced cement concrete, two-hybrid fibers reinforced concrete, and multi-scale hybrid fibers reinforced cement concrete containing various basalt fiber dosage. It is reported that the optimal mechanical properties for multi-scale hybrid fiber reinforced cement concrete was noticed with 0.8% basalt fiber dosage, calcium carbonate whisker of 1%, and steel fiber of 0.25% dosage [41].

The findings showed that if the mass ratio of polypropylene fiber to basalt fiber is 2:1 and the total mass is 6 kg/m^3, the favorable hybrid effect is more remarkable for both compressive test and splitting tensile test. Compared to the concrete with exclusion fibers, the splitting tensile strength was risen by 24%, while the compressive strength was risen by 14%. Micro basalt fiber and macro polypropylene fiber fracture resistance could not be exchanged. Fibers with various dimensions and elastic modulus perform vital roles in varying states of composites. Using hybrid basalt polypropylene fibers in cement concrete composites showed an improvement in compressive strength and splitting tensile strength [42]. The hybrid fiber reinforced cement concrete was composed by adding sisal fiber, polypropylene fiber, and banana fiber to investigate the durability and mechanical properties of cement concrete composites. Enhancement was observed by 24.3% and 14.9% for compressive strength of M3 mix when comparison with normal cement concrete composites at the curing age of 28 days. Similarly, an increment was recorded 47.54% and 37.19% of splitting tensile strength for M3 mix when compared with normal cement concrete composites at the curing age of 7 and 28 days, respectively. Also, improvement was observed with the maximum value of 5.58 N/mm^2 and 10.9 N/mm^2 of flexure strength for M3 mix when compared with normal cement concrete composites at the curing age of 7 and 28 days, respectively [43]. Polypropylene, carbon, and aramid fibers can efficiently increase the initial mechanical properties of hybrid fiber reinforced cement concrete composites, particularly for the flexure and tensile strengths. Although the enrichment in tensile strength was associated with the polypropylene fiber aspect ratio, on the other hand, the aspect ratio of aramid fiber contributed to improving the flexural and compressive behaviors. A minor effect of fibers aspect ratio was reported concerning to the initial phase of hybrid fiber reinforced cement concrete composites. Meanwhile, tensile strength is almost 15 times the compressive strength, which is equivalent to plain concrete having 28 days curing age [44]. It was concluded from the results of an experimental study that there was a direct effect of volume content of the fibers on tensile and flexure strength and improvement in the strength of first cracks due to the inclusion of fibers was observed. All other combinations of steel-polypropylene hybrid fiber reinforced cement concrete composites showed effective synergy to the strengths of splitting tensile and flexure strength. Therefore, hybridization of polypropylene/steel is more beneficial for introducing the reinforcement in the structural elements [45]. Table 1 is the representation of raw material, mix proportion and increased strengths of hybrid fiber reinforced concrete.

Table 1. Raw material, mix proportion, studied properties and increased strengths of HFRC [22], [46], [44], [47].

Sr. No.	Raw material	Mix proportion	Strength increment
1	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Polypropylene (P-P), Steel (S) fiber and Crumb Rubber (C-R).	1: 1.68: 1.15: 0: 0: 0 & w/c ratio 0.45. P-P-F length = 3 mm. S-F length 21 mm. Hybrid Fiber (H-F) = (P-P+S) content = (0+1, 0.1+0.9, 0.175+0.825, 0.25+0.75, 1+0 %). C-R = 20%. Total volume fraction = (1 %). By volume of PC.	C-S = Increased 48.02 MPa with 0.1+0.9 % H-F content as per PC. C-S = Increased 33.94 MPa with 0.1+0.9 % R-H-F content as per R-C. S-T-S= Increased 5.09 MPa with 0.1+0.9 % H-F content as per PC.
2	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Macro Polypropylene (M-P-P) and Basalt (B) fiber.	1: 2.34: 3.09: 0: 0: 0 & w/c ratio 0.68. 1: 0.96: 2.21: 0: 0: 0 & w/c ratio 0.44. M-P-P-F length = 60 mm. B-F length = 20mm. M-P-P-F content = (0, 0.3, 0.7, 0.1 %). Hybrid Fiber (H-F) = (P-P+B) content = (0+0.1, 0.3+0.1, 0.7+0.1, 0.1+0.1 %). By volume of PC.	C-S = Increased 10%. F-S = Increased 20%.
3	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Polypropylene (P-P), Carbon (C), and Aramid (A) fiber.	1: 1.12: 2.27: 0: 0: 0 & w/c ratio 0.39. P-P-F length = 9, 12, 18 mm. C-F length = 1.7 mm. A-F length = 5, 7, 9 ,11 mm Hybrid Fiber (H-F) = (P-P+C+A) content = (0.04+0.04+0.04 %). By volume of PC.	C-S = Increased 18.3%. F-S= Increased 38.7%. S-T-S= Increased 40.8%. With H-F content as per PC.
4	Cement, Sand, Aggregate, Silica Fume, Fly Ash, Slag, Water, Polypropylene (P-P) and Basalt (B) fiber.	1: 2.27: 2.91: 0: 0: 0 & w/c ratio 0.36. P-P-F length =50 mm. B-F length =19 mm. Hybrid Fiber (H-F) = (P-P+B) content = (0.63+0, 0+0.22, 0.51+0.04, 0.42+0.07, 0.32+0.11, 0.21+0.15, 0.13+0.17 %). By volume of PC.	C-S = Increased with H-F. C-S = Increased 14% with 0.63+0 % H-F content as per PC. T-S = Increased 24% with 0.63+0 % H-F content as per PC.
Note: Compressive-strength (C-S); Flexural-strength (F-S); Split-tensile-strength (S-T-S).			

V. SUSTAINABILITY WITH HFRC

The construction sector uses a lot of natural resources and has a lot of negative environmental consequences. Building block production accounts for about 40% of total energy consumption, greenhouse gas emissions for 30%, freshwater consumption for 17%, harvested wood for 25%, and 45% to 65% disposal in landfills, as reported by the world business council for sustainable development [48-51]. Consequently, controlling environmental problems in industry of construction has become a significant concern. Green construction, which aims to decrease the harmful effects of buildings construction on humans and the environment, has lately gained a lot of attention [52]. Therefore, the production of the fibers as reported in current research requires a large quantity of energy and raw materials, i.e., fossil fuel [53, 54]. The cost of the composite material rises as the sustainability is reduced, i.e., unavoidable greenhouse gas emissions while manufacturing of steel. [55]. To minimize the environmental effects and warning of deficiency by using the natural resource, an advanced number of researches have been conducted to utilizing the recycled materials as the fiber reinforcing in cement based composites. Similarly, the reproduction of the materials from the real life of tires; one of the most recent endeavors, for example, is to replace steel and polymeric fibers with new manufacturing fibers. Around 500 million discarded tires are reported to be improperly disposed-off, with few landfill disposal locations being one of the most significant dangers to human civilization [56, 57]. The massive volume of solid tire wastes might offer many environmental impacts, such as igniting fire and viruses etc. [58]. Furthermore, steel, polymer fibers, and rubber particles could be recoverable through particular processing phases. As a result, there may be a method to efficiently recycle a large amount of discarded tires for utilization in cementitious composites worldwide [59].

VI. CONCLUSIONS

In this paper, a review has been done. The purpose of this research is to explore the use of natural fibers hybridization with artificial fibers in cementitious composites for sustainable construction. This paper will provide a brief summary about the benefits of using natural hybrid fibers for sustainable construction. Also, it will promote the potential use of hybrid fibers in cementitious composites. One of the most important research fields in engineering is the production of environmentally sustainable materials. Concrete is a high-demand material for the building and construction sector in civil engineering and related disciplines. By minimizing the environmental toxicity effect and natural resource scarcity caused by landfilled solid waste, the appropriate use of hybrid fibers in concrete obtained from natural resources may enhance the building industry's sustainability. The goal of the current review is to discuss the hybridization effect of synthetic fiber (polypropylene) with natural fibers for the flexure, compressive, and splitting tensile strengths of hybrid fiber reinforced cementitious composites. After a detailed literature review, it was found that the use of hybrid fibers in cementitious composites can improve the mechanical properties. Further, hybrid fiber reinforced cement based composites provide strong resistance to the formation and generation of cracks at different level as per their scale size. Hence, the addition of hybrid polypropylene fibers with natural fibers could be an alternate solution for minimizing dangerous environmental effects with cost effectiveness in construction industry. Further study should be carried out on the utilization of artificial fibers with natural fibers hybridization in cement based composites for improved mechanical behavior as well as reduction in environmental pollution and global warming by utilizing natural resources. It is suggested to investigate the durability of hybrid fibers as a concrete fiber reinforcement. Furthermore, the study on the overall pore shape and pore continuity of the hybrid fibers material for the concrete application need to be explored in future.

VII. ACKNOWLEDGMENTS

The author would like to thank Engr. Prof. Dr. Majid Ali for his kind support and guidance.

VIII. REFERENCES

[1] M. K. Yew, I. Othman, M. C. Yew, S. Yeo, and H. Mahmud, "Strength properties of hybrid nylon-steel and polypropylene-steel fibre-reinforced high strength concrete at low volume fraction," *International Journal of Physical Sciences,* vol. 6, pp. 7584-7588, 2011.

[2] E. Awwad, M. Mabsout, B. Hamad, M. T. Farran, and H. Khatib, "Studies on fiber-reinforced concrete using industrial hemp fibers," *Construction and Building Materials,* vol. 35, pp. 710-717, 2012.

[3] T. Lecompte, A. Perrot, A. Subrianto, A. Le Duigou, and G. Ausias, "A novel pull-out device used to study the influence of pressure during processing of cement-based material reinforced with coir," *Construction and Building Materials,* vol. 78, pp. 224-233, 2015.

[4] L. Yan, "Plain concrete cylinders and beams externally strengthened with natural flax fabric reinforced epoxy composites," *Materials and Structures,* vol. 49, pp. 2083-2095, 2016.

[5] P. Bordes, E. Pollet, and L. Avérous, "Nano-biocomposites: biodegradable polyester/nanoclay systems," *Progress in Polymer Science,* vol. 34, pp. 125-155, 2009.

[6] L. Yan, N. Chouw, and K. Jayaraman, "On energy absorption capacity, flexural and dynamic properties of flax/epoxy composite tubes," *Fibers and Polymers,* vol. 15, pp. 1270-1277, 2014.

[7] A. A. Azeez, K. Y. Rhee, S. J. Park, and D. Hui, "Epoxy clay nanocomposites–processing, properties and applications: A review," *Composites Part B: Engineering,* vol. 45, pp. 308-320, 2013.

[8] S. Yin, R. Tuladhar, F. Shi, M. Combe, T. Collister, and N. Sivakugan, "Use of macro plastic fibres in concrete: A review," *Construction and Building Materials,* vol. 93, pp. 180-188, 2015.

[9] A. Sadrmomtazi, B. Tahmouresi, and A. Saradar, "Effects of silica fume on mechanical strength and microstructure of basalt fiber reinforced cementitious composites (BFRCC)," *Construction and Building Materials,* vol. 162, pp. 321-333, 2018.

[10] A. Enfedaque, D. Cendón, F. Gálvez, and V. Sánchez-Gálvez, "Analysis of glass fiber reinforced cement (GRC) fracture surfaces," *Construction and Building Materials,* vol. 24, pp. 1302-1308, 2010.

[11] S. Fallah and M. Nematzadeh, "Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume," *Construction and building materials,* vol. 132, pp. 170-187, 2017.

[12] R. Abaeian, H. P. Behbahani, and S. J. Moslem, "Effects of high temperatures on mechanical behavior of high strength concrete reinforced with high performance synthetic macro polypropylene (HPP) fibres," *Construction and Building Materials,* vol. 165, pp. 631-638, 2018.

[13] H. A. Toutanji, "Properties of polypropylene fiber reinforced silica fume expansive-cement concrete," *Construction and Building Materials,* vol. 13, pp. 171-177, 1999.

[14] J. Wei and C. Meyer, "Degradation mechanisms of natural fiber in the matrix of cement composites," *Cement and Concrete Research,* vol. 73, pp. 1-16, 2015.

[15] N. Saba, M. Paridah, and M. Jawaid, "Mechanical properties of kenaf fibre reinforced polymer composite: A review," *Construction and Building materials,* vol. 76, pp. 87-96, 2015.

[16] L. Yan, N. Chouw, and K. Jayaraman, "Flax fibre and its composites–A review," *Composites Part B: Engineering,* vol. 56, pp. 296-317, 2014.

[17] D. Hannant, "Durability of polypropylene fibers in Portland cement-based composites: eighteen years of data," *Cement and Concrete Research,* vol. 28, pp. 1809-1817, 1998.

[18] A. Richardson, "Electrical properties of Portland cement, with the addition of polypropylene fibres–regarding durability," *Structural Survey,* 2004.

[19] D. Wang, Y. Ju, H. Shen, and L. Xu, "Mechanical properties of high performance concrete reinforced with basalt fiber and polypropylene fiber," *Construction and Building Materials,* vol. 197, pp. 464-473, 2019.

[20] S. Jalasutram, D. R. Sahoo, and V. Matsagar, "Experimental investigation of the mechanical properties of basalt fiber‐reinforced concrete," *Structural Concrete,* vol. 18, pp. 292-302, 2017.

[21] W. He, X. Kong, Y. Fu, C. Zhou, and Z. Zheng, "Experimental investigation on the mechanical properties and microstructure of hybrid fiber reinforced recycled aggregate concrete," *Construction and Building Materials,* vol. 261, p. 120488, 2020.

[22] E. A. Alwesabi, B. A. Bakar, I. M. Alshaikh, and H. M. Akil, "Experimental investigation on mechanical properties of plain and rubberised concretes with steel–polypropylene hybrid fibre," *Construction and Building Materials,* vol. 233, p. 117194, 2020.

[23] M. Ali and N. Chouw, "Coir fibre and rope reinforced concrete beams under dynamic loading," in *Annual Australian Earthquake Engineering Society Conference,"Newcastle Earthquake–20 years on,* 2009.

[24] M. Ali, "Use of coconut fibre reinforced concrete and coconut-fibre ropes for seismic-resistant construction," *Materiales de Construcción,* vol. 66, p. 073, 2016.

[25] M. Ali, "Seismic performance of coconut-fibre-reinforced-concrete columns with different reinforcement configurations of coconut-fibre ropes," *Construction and Building Materials,* vol. 70, pp. 226-230, 2014.

[26] M. Ali, "Role of post-tensioned coconut-fibre ropes in mortar-free interlocking concrete construction during seismic loadings," *KSCE Journal of Civil Engineering,* vol. 22, pp. 1336-1343, 2018.

[27] V. Afroughsabet and T. Ozbakkaloglu, "Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers," *Construction and building materials,* vol. 94, pp. 73-82, 2015.

[28] L. Betterman, C. Ouyang, and S. P. Shah, "Fiber-matrix interaction in microfiber-reinforced mortar," *Advanced Cement Based Materials,* vol. 2, pp. 53-61, 1995.

[29] N. Banthia, F. Majdzadeh, J. Wu, and V. Bindiganavile, "Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear," *Cement and Concrete Composites,* vol. 48, pp. 91-97, 2014.

[30] P. Song, J. Wu, S. Hwang, and B. Sheu, "Statistical analysis of impact strength and strength reliability of steel–polypropylene hybrid fiber-reinforced concrete," *Construction and building materials,* vol. 19, pp. 1-9, 2005.

[31] A. A. Nia, M. Hedayatian, M. Nili, and V. A. Sabet, "An experimental and numerical study on how steel and polypropylene fibers affect the impact resistance in fiber-reinforced concrete," *International Journal of Impact Engineering,* vol. 46, pp. 62-73, 2012.

[32] M. Khan and M. Cao, "Effect of hybrid basalt fibre length and content on properties of cementitious composites," *Magazine of Concrete Research,* pp. 1-12, 2020.

[33] R. Ralegaonkar, H. Gavali, P. Aswath, and S. Abolmaali, "Application of chopped basalt fibers in reinforced mortar: A review," *Construction and building materials,* vol. 164, pp. 589-602, 2018.

[34] S. Spadea, I. Farina, A. Carrafiello, and F. Fraternali, "Recycled nylon fibers as cement mortar reinforcement," *Construction and Building Materials,* vol. 80, pp. 200-209, 2015.

[35] A. Izaguirre, J. Lanas, and J. I. Alvarez, "Effect of a polypropylene fibre on the behaviour of aerial lime-based mortars," *Construction and Building Materials,* vol. 25, pp. 992-1000, 2011.

[36] H. Zhong and M. Zhang, "Experimental study on engineering properties of concrete reinforced with hybrid recycled tyre steel and polypropylene fibres," *Journal of Cleaner Production,* p. 120914, 2020.

[37] F. Qamar, T. Thomas, and M. Ali, "Use of natural fibrous plaster for improving the out of plane lateral resistance of mortarless interlocked masonry walling," *Construction and Building Materials,* vol. 174, pp. 320-329, 2018.

[38] Z. Tang, M. Ali, and N. Chouw, "Residual compressive and shear strengths of novel coconut-fibre-reinforced-concrete interlocking blocks," *Construction and Building Materials,* vol. 66, pp. 533-540, 2014.

[39] M. U. Farooqi and M. Ali, "Contribution of plant fibers in improving the behavior and capacity of reinforced concrete for structural applications," *Construction and Building Materials,* vol. 182, pp. 94-107, 2018.

[40] T. Hussain and M. Ali, "Improving the impact resistance and dynamic properties of jute fiber reinforced concrete for rebars design by considering tension zone of FRC," *Construction and Building Materials,* vol. 213, pp. 592-607, 2019.

[41] M. Khan, M. Cao, and M. Ali, "Cracking behaviour and constitutive modelling of hybrid fibre reinforced concrete," *Journal of Building Engineering,* vol. 30, p. 101272, 2020.

[42] Z. Deng, X. Liu, X. Yang, N. Liang, R. Yan, P. Chen*, et al.*, "A study of tensile and compressive properties of hybrid basalt‐polypropylene fiber‐reinforced concrete under uniaxial loads," *Structural Concrete,* vol. 22, pp. 396-409, 2021.

[43] E. Palanisamy and M. Ramasamy, "Dependency of Sisal and Banana Fiber on Mechanical and Durability Properties of Polypropylene Hybrid Fiber Reinforced Concrete," *Journal of Natural Fibers,* pp. 1-11, 2020.

[44] H. Huang, Y. Yuan, W. Zhang, and L. Zhu, "Experimental study on the mechanical properties and the microstructure of hybrid‐fiber‐reinforced concrete under an early stage," *Structural Concrete,* vol. 21, pp. 1106-1122, 2020.

[45] N. K. Singh and B. Rai, "Assessment of synergetic effect on microscopic and mechanical properties of steel‐polypropylene hybrid fiber reinforced concrete," *Structural Concrete,* vol. 22, pp. 516-534, 2021.

[46] F. Shi, T. M. Pham, H. Hao, and Y. Hao, "Post-cracking behaviour of basalt and macro polypropylene hybrid fibre reinforced concrete with different compressive strengths," *Construction and Building Materials,* vol. 262, p. 120108, 2020.

[47] Z. Deng, X. Liu, X. Yang, N. Liang, R. Yan, P. Chen*, et al.*, "A study of tensile and compressive properties of hybrid basalt‐polypropylene fiber‐reinforced concrete under uniaxial loads," *Structural Concrete,* 2020.

[48] B. Sisson and C. Van Aerschot, "Energy Efficiency Buildings: Business realities and opportunities," *World Business Council for Sustainable Development (WBCSD),* 2008.

[49] U. Sbci, "Buildings and climate change: Summary for decision-makers," *United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris,* pp. 1-62, 2009.

[50] C. Say and A. Wood, "Sustainable rating systems around the world," *Council on Tall Buildings and Urban Habitat Journal (CTBUH Review),* vol. 2, pp. 18-29, 2008.

[51] F. Smith Peter, "Architecture in a Climate of Change, A guide to sustainable design. ed," ed: ArchitectUral Press, Oxford, 2005.

[52] A. Sev, "A comparative analysis of building environmental assessment tools and suggestions for regional adaptations," *Civil Engineering and Environmental Systems,* vol. 28, pp. 231-245, 2011.

[53] M. Mastali, A. Dalvand, A. Sattarifard, Z. Abdollahnejad, and M. Illikainen, "Characterization and optimization of hardened properties of self-consolidating concrete incorporating recycled steel, industrial steel, polypropylene and hybrid fibers," *Composites Part B: Engineering,* vol. 151, pp. 186-200, 2018.

[54] O. Onuaguluchi and N. Banthia, "Scrap tire steel fiber as a substitute for commercial steel fiber in cement mortar: engineering properties and cost-benefit analyses," *Resources, Conservation and Recycling,* vol. 134, pp. 248-256, 2018.

[55] K. Liew and A. Akbar, "The recent progress of recycled steel fiber reinforced concrete," *Construction and Building Materials,* vol. 232, p. 117232, 2020.

[56] B. S. Thomas and R. C. Gupta, "A comprehensive review on the applications of waste tire rubber in cement concrete," *Renewable and Sustainable Energy Reviews,* vol. 54, pp. 1323-1333, 2016.

[57] J. Wang, Q. Dai, R. Si, and S. Guo, "Mechanical, durability, and microstructural properties of macro synthetic polypropylene (PP) fiber-reinforced rubber concrete," *Journal of Cleaner Production,* vol. 234, pp. 1351-1364, 2019.

[58] H. Zhong, E. W. Poon, K. Chen, and M. Zhang, "Engineering properties of crumb rubber alkali-activated mortar reinforced with recycled steel fibres," *Journal of Cleaner Production,* vol. 238, p. 117950, 2019.

[59] S. Gigli, D. Landi, and M. Germani, "Cost-benefit analysis of a circular economy project: a study on a recycling system for end-of-life tyres," *Journal of Cleaner Production,* vol. 229, pp. 680-694, 2019.