Paper ID: BECM 0127

Enhancement of Concrete's Flexibility Using Local Ingredients

F. Abdullah[1], J. A. Mouri[2], T. A. Jui[3]

[1]Department of Building Engineering & Construction Management, RUET, Bangladesh (abdullah@becm.ruet.ac.bd)
[2]Department of Building Engineering & Construction Management, RUET, Bangladesh (jemimara22@gmail.com)
[3]Department of Building Engineering & Construction Management, RUET, Bangladesh (tasmiajui999@gmail.com)

Abstract

The perfect blending of creativity and pragmatism is the beauty of engineering. Engineered Cementitious Composites (ECC) are a unique type of long-lasting, tensile, and ductile building materials. They are made by precisely combining cement, water, sand, and fibers, usually steel or synthetic. By boosting the tensile strength and ductility of the composite, the inclusion of fibers enhances its mechanical qualities, reducing the likelihood of cracking and enhancing the material's overall longevity. The utilization of regional natural fibers (NFs), such as jute and coir, in the production of ECC, might be a game-changer in a future where sustainability is crucial. By evaluating their performance with that of steel and synthetic fibers (SFs) in ECC, this study seeks to demonstrate the viability of these NFs. NFs are environmentally friendly affordable, thin, reusable, thermally efficient, and corrosion-resistant. NFs in ECC will improve mechanical characteristics and promote green construction.

Keywords: *Building materials; sustainability; natural fibers; flexibility; eco-friendly.*

1 Introduction

Standard concrete buildings have been tending to cracking and deterioration owing to their low tensile strength and fragility for a long time (Cai et al. 2014; Luo et al. 2019; Yang et al. 2008). ECC were an obvious option for enhancing the mechanical properties of concrete construction. The high tensile strength and special bridging property of ECC make it resistant to the initiation and propagation of cracks. Customizing materials for the appropriate ductility with strain hardening behavior in the hardened state is a significant part of ECC fabrication and modification (Abdulkadir et al. 2021). Polyvinyl Alcohol (PVA) fibers manufactured by Kuraray Co. Ltd. in Japan account for around 2% of the volume fraction utilized in the manufacturing of ECC, as reported in the literature. Further research into the impact of fiber length on ECC tensile response revealed that PVA in length of 18 mm long fiber reinforcement yielded the optimum tensile performance (Ma et al. 2015; Qin et al. 2020). However, the price of Japanese PVA fibers is around $4.80 per kg which is 5 times more than the local Bangladeshi kind. Over 90% of the expense of ECC may be traced back to the use of PVA fiber. In order to encourage wider adoption of ECC in Bangladesh, it seems sense to make use of locally sourced ingredients, such as NFs that is easily accessible and inexpensive. Since the domestic fiber lacks the physical and mechanical properties of the Kuraray PVA fiber, it is important to optimize the mix design and preparation (Anil et al. 2016; Luo et al. 2019) in order to fine-tune the key parameters such as the fiber volume fraction in engineering practice to meet the needs of industry (Li et al. 2017; Sherzer et al. 2020). Further, accurate numerical modeling may aid in enhancing ECC material design and its performance in real-world structures.

ECC, developed by Professor Victor C. Li at the University of Michigan in 1993, is known for its high ductility (3-5%) and moderate tensile strength (4-6 MPa). The ECC's mix no longer includes coarse aggregates. In general, ECCs exhibit two distinctive features: the production of numerous micro cracks and strain hardening behavior. After the first cracking occurs, the strain hardening characteristic causes the load to increase along with the tensile deformation (Li 2008). Not only are ECCs excellent for buildings in seismically active areas, but they are also impact and explosion resistant (Yang and Li 2005).

Fibers improve cement-based composites flexural and tensile characteristics and inhibit fracture development and propagation by bridging micro cracks (Kim et al. 2008). Due to greater flexural, tensile, and fracture resistance, steel fiber-reinforced cementitious composites are used in plants and tunnels. Steel fibers high specific gravity and stiffness may cause concrete pump tube breakage, shotcrete rebound volume increase, and fiber corrosion, reducing durability. Thus, organic fibers with steel-like mechanical characteristics but without corrosion should be developed and used. Extracting NFs requires little energy (Li et al. 2004). Jute, coir, sisal, bamboo, date, cotton, malva, hemp, banana, sugarcane, flax, and palm are some of the examples of NFs.

In order to replace SFs and steel rebar as structural reinforcement, engineering businesses have had to come up with novel, dependable, and environmentally friendly materials because to rising public knowledge and concern about industrial pollution (Saba et al. 2015; Wei and Meyer 2015; Yan et al. 2014). Nanotechnology has revived interest in NFs reinforced polymer composites as next-generation structural materials (Bordes et al. 2009). A sustainable concrete business may be developed by replacing steel rebar with NFs in construction and building. Lignin, hemicellulose, and cellulose are widely recognized as the primary constituents of NFs. These fibers derive their mechanical properties from the abundance of cellulose and the micro fibrillary angles present within their structure. (Gaceva et al. 2007). When compared to other NFs, jute stands itself as a very cost-effective option. About 65%-75% cellulose, 13.6-20.4% hemicellulose, and 8% microfibrils make up a jute fiber's makeup. (Williams and Wool 2000). With the highest tensile strength and most distinguishable microstructure among all NFs, jute fiber is the best candidate for substituting SFs in composite materials (Patel and Patel 2018). Due to their low cost, durability, and other benefits, coir fibres are extensively used for floor furnishing materials, yarn, rope, etc. (Zaman and Beg 2014). Coir is crucial to tropical economies like India, Bangladesh, Sri Lanka, Thailand, etc. Coir's robustness, flexibility, fungal and rot resistance, moth-proof, and good temperature and sound insulation make it a popular commercial and industrial material (Haque et al. 2010). Coir is mostly multicellular, with 30–300 cells per cross section. Coir cells are noncrystalline cellulose-lignin complexes with crystalline cellulose organized helically (Zaman and Beg 2014). Coir fibre has the greatest elongation at break among NFs and can withstand 4–6 times higher strain (Munawar et al. 2007; Satyanarayana et al. 1990; Satyanarayana et al. 1981).

NFs have many benefits over synthetic ones, including high yield, cheap processing cost, and low density, in addition to being renewable and recyclable. The production and use of NFs also generate and uses almost half as much raw material as every other raw material sector combined. It takes a lot of energy and produces a lot of greenhouse emissions when regular Portland cement is made. The researcher has looked at finding other construction materials due to excessive energy consumption and CO_2 emissions (Huang et al. 2018; Li, Huang, and Xu 2016; Yu et al. 2018). Concrete reinforcing materials made from NFs, rather than SFs, have been the preferred choice for decades (Matheu et al. 2015) due to rising environmental awareness and the desire to create eco-friendly products. The current construction sector is not sustainable, thus the hunt for sustainable alternatives has attracted a lot of attention. The primary goals of this study are to maintain a stable economic structure and to increase the stiffness of reinforced concrete by using both natural and SFs. This study measures the compressive strength and split tensile strength of concrete with varying contents of NFs to investigate the impact of fiber content on these parameters.

2 Experimental Program

The raw materials selected for this study include cement, sand, and various types of fibers. The test procedure involves evaluating the mechanical properties of the ECC mixtures, such as compressive strength and flexural properties. The aim is to investigate the performance and behavior of ECC reinforced with different types of fibers. Standardized testing methods based on ASTM standards are employed to ensure accurate and reliable results.

2.1 Specimen Preparation

Fiber reinforcing effectiveness was evaluated by comparing two types of specimens: an ECC mixture and an ECC matrix devoid of fiber. In this research work, ECC mixtures were developed using four different types of fibers: steel, nylon, jute, and coir fiber (Each 18 mm in length). A comparison was made with a normal concrete mixture for reference. The mixing ratio for all mixtures was maintained at 1:2 (cement to aggregate), and the fibers were added by weight of cement at predetermined percentages. The experimental program consisted of two stages, focusing on mechanical property tests. In the first stage, standard 150 mm × 300 mm cylindrical specimens were prepared for assessing the compressive strength of the concrete, following the guidelines outlined in ASTM C39. These specimens were subjected to a uniaxial compression load until failure, and the compressive strength values were recorded. Furthermore, flexure tests of concrete slabs were performed according to ASTM C293 to assess the flexural properties of the ECC mixtures. The slabs were subjected to a bending load until failure, and the flexural strength values were recorded. In addition to the mechanical property tests, scanning electron microscopy (SEM) and X-ray diffraction (XRD) tests were conducted to analyze the microstructural characteristics and chemical composition of the ECC mixtures. The results obtained from these tests will contribute to understanding the influence of fiber type on the performance of ECC and its potential as a sustainable and durable construction material.

2.2 Compressive Strength

The compressive strength test results obtained after 28 days of curing were analyzed to evaluate the performance of each fiber type at various fiber percentages. The results (Figure 1) revealed interesting findings regarding the influence of different fibers on the compressive strength of ECC. Among the NFs, jute demonstrated the highest enhancement in compressive strength, with values ranging from 21.50 MPa to 18.50 MPa at fiber contents of 1% to 2%. Coir fibers also exhibited positive effects on compressive strength, albeit to a slightly lesser extent. The steel fibers displayed consistent compressive strength values, showcasing their reliability as a reinforcing material. On the other hand, the impact of nylon fibers on compressive strength was relatively limited. These findings highlight the potential of utilizing jute and coir fibers as effective alternatives to traditional steel fibers in ECC applications. The study's results provide valuable insights into the performance of different fiber types in enhancing compressive strength and contribute to the understanding of fiber-reinforced ECC. The research findings suggest that incorporating NFs, particularly jute and coir, into ECC mixtures can lead to significant improvements in compressive strength. This presents promising opportunities for sustainable and cost-effective construction practices, especially in regions where these NFs are abundantly available. Further exploration of these NFs in ECC formulations can provide additional insights into their long-term durability and structural performance. Additionally, investigating the durability and long-term behavior of ECC with NFs reinforcement would be valuable for practical implementation in real-world construction scenarios.

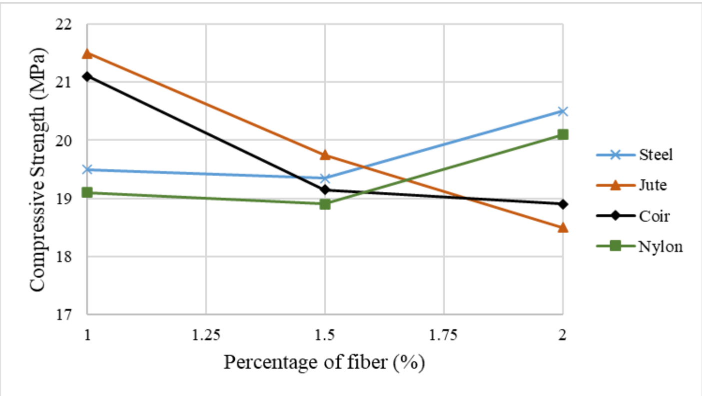

Figure 1. Compressive strength of ECC for different percentage of fiber.

2.3 Flexure Strength

The flexural strength test results obtained were examined to evaluate the performance of each fiber type at varying fiber percentages. The results (Figure 2) revealed noteworthy insights into the impact of different fibers on the flexural strength of ECC. Among the fibers tested, steel displayed consistent flexural strength values, highlighting its reliability as a reinforcement material. Jute and coir fibers exhibited moderate improvements in flexural strength, while the impact of nylon fibers on flexural strength was relatively limited. These findings contribute to the understanding of the influence of different fiber types on the flexural strength of ECC. The results suggest that steel fibers remain a robust choice for enhancing flexural strength, while jute and coir fibers show potential as alternative reinforcement options. However, further research is needed to explore their long-term durability and structural performance. The study's findings provide valuable insights for the development of ECC with improved flexural strength and contribute to the advancement of sustainable and resilient construction practices. Future research could focus on investigating additional mechanical properties to gain a comprehensive understanding of ECC's overall performance when reinforced with different fiber types.

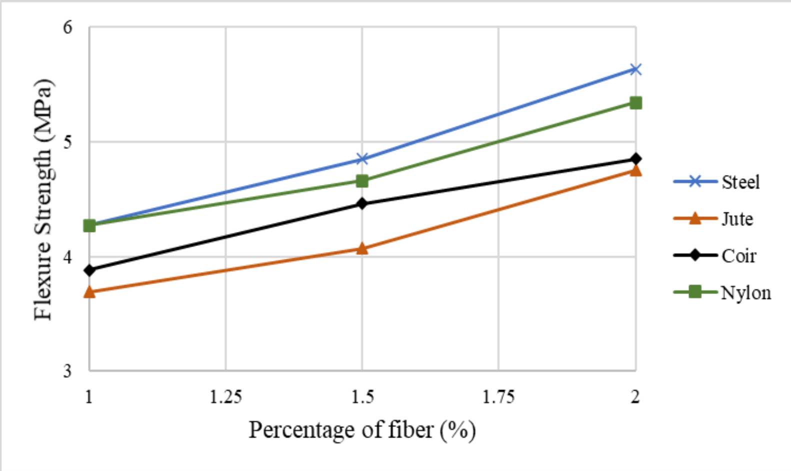

Figure 2. Flexure strength of ECC for different percentage of fiber.

2.4 Scanning Electron Microscopy (SEM) Test

The scanning electron microscopy (SEM) analysis of the jute fiber reinforced ECC specimens revealed a distinct interfacial bond between the jute fibers and the cementitious matrix. The SEM images (Figure 3) displayed a well-distributed and uniform dispersion of jute fibers throughout the ECC matrix, indicating good fiber-matrix interaction. The jute fibers exhibited a rough and irregular surface morphology, which contributed to enhanced mechanical interlocking with the cementitious matrix. These findings suggest that jute fibers can effectively reinforce ECC and improve its crack resistance and toughness. The SEM analysis of the coir fiber reinforced ECC specimens exhibited a similar interfacial bond as observed in the jute fiber specimens. The SEM images revealed a homogeneous distribution of coir fibers within the ECC matrix, indicating effective fiber-matrix integration. The coir fibers exhibited a porous and fibrous structure, which facilitated the mechanical interlocking with the cementitious matrix. The SEM results indicate that coir fibers have the potential to enhance the mechanical properties and durability of ECC. The SEM examination of the nylon fiber reinforced ECC specimens displayed a distinct interfacial bond between the nylon fibers and the cementitious matrix. The SEM images revealed a uniform dispersion of nylon fibers throughout the ECC matrix, indicating good fiber-matrix adhesion. The nylon fibers exhibited a smooth and glossy surface morphology, allowing for efficient load transfer between the fibers and the matrix. These findings suggest that nylon fibers can significantly contribute to the mechanical strength and crack resistance of ECC.

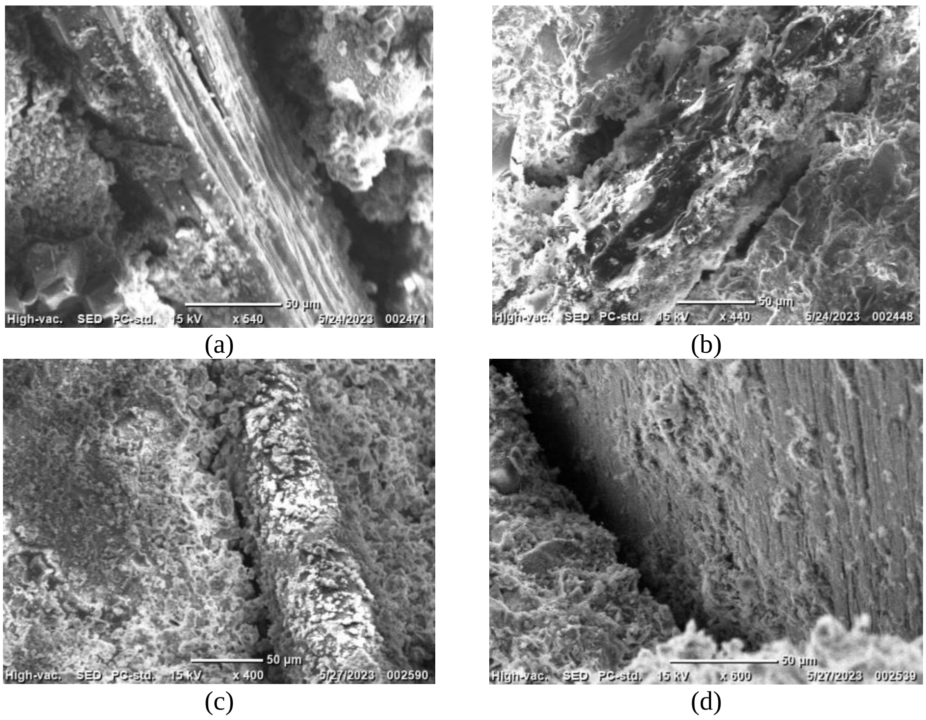

Figure 3. SEM view of ECC; (a) jute fiber (b) coir fiber (c) nylon fiber (d) steel fiber.

The SEM analysis of the steel fiber reinforced ECC specimens demonstrated a strong interfacial bond between the steel fibers and the cementitious matrix. The SEM images exhibited a well-dispersed arrangement of steel fibers within the ECC matrix, indicating excellent fiber-matrix compatibility. The steel fibers displayed a smooth and metallic surface texture, enabling effective stress transfer and load-bearing capacity. The SEM results indicate that steel fibers can provide significant reinforcement to ECC, enhancing its mechanical properties and resistance to cracking.

2.5 X-Ray Diffraction (XRD) Test

The X-ray diffraction (XRD) analysis conducted on the engineered cementitious composite (ECC) provided valuable insights into the crystalline structure and mineralogical composition of the material. The XRD patterns (Figure 4) revealed the presence of various phases, including calcium silicates, calcium hydroxide, and other hydration products. The diffraction peaks corresponding to these phases were well-defined and consistent, indicating the formation of a dense and well-hydrated cementitious matrix in the ECC. The results suggest that the inclusion of fibers in ECC contributes to the refinement of the cementitious matrix and the formation of a more interconnected and crack-resistant structure. Overall, the XRD analysis supports the potential of fiber-reinforced ECC for achieving enhanced mechanical performance and durability in construction applications.

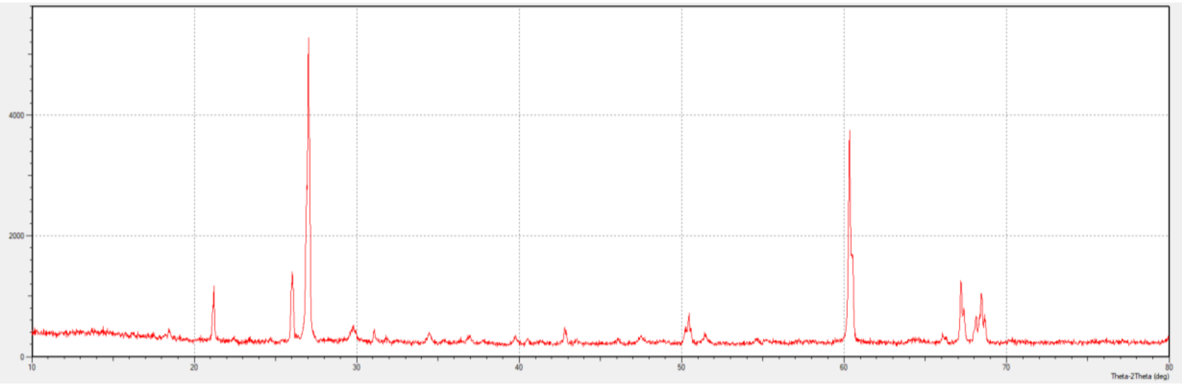

Figure 4. XRD value of ECC.

3 Conclusions

The study demonstrated that the addition of natural and synthetic fibers to cement-based composites significantly enhances their mechanical properties. Fibers such as steel, nylon, jute and coir act as reinforcement, improving the flexural and tensile properties of the composites. However, fibers—natural or artificial improve ECC post-peak reactivity and reduce brittle failure. Moreover, the use of steel fiber-reinforced cementitious composites leads to exceptional flexural and tensile strength, toughness, and crack resistance, making them highly suitable for demanding applications in tunnels and plant structures. The SEM test played a crucial role in understanding the microstructure of the cement-based composites. By observing the samples under the microscope, it became evident that the fibers effectively bridge micro cracks, thereby preventing crack initiation and propagation within the matrix. This bridging effect significantly enhances the overall performance and durability of the composites. The XRD test analysis provided valuable insights into the mineral composition and crystalline structure of the composites. It not only confirmed the presence of various fibers, including mineral and NFs, but also demonstrated the effectiveness of fiber reinforcement in controlling brittle failure and improving the post-peak response of the composites. Furthermore, the test results emphasized the need for exploring organic fibers that possess mechanical properties similar to steel fibers, without the drawbacks of high specific gravity, stiffness, and corrosion.

References

Abdulkadir, Isyaka, Bashar S. Mohammed, M. S. Liew, and M. M.A. Wahab. 2021. "Modelling and Multi-Objective Optimization of the Fresh and Mechanical Properties of Self-Compacting High Volume Fly Ash ECC (HVFA-ECC) Using Response Surface Methodology (RSM)." *Case Studies in Construction Materials* 14.

Anil, Özgür, Cengizhan Durucan, R. Tuğrul Erdem, and M. Arif Yorgancilar. 2016. "Experimental and Numerical Investigation of Reinforced Concrete Beams with Variable Material Properties under Impact Loading." *Construction and Building Materials* 125: 94–104.

Bordes, Perrine, Eric Pollet, and Luc Avérous. 2009. “Nano-Biocomposites: Biodegradable Polyester/Nanoclay Systems.” *Progress in Polymer Science (Oxford)* 34(2): 125–55.

Cai, Jingming, Jinlong Pan, and Fang Yuan. 2014. “Experimental and Numerical Study on Flexural Behaviors of Steel Reinforced Engineered Cementitious Composite Beams.” *Journal of Southeast University (English Edition)* 30(3): 330–35.

G. Bogoeva-Gaceva, M. Avella, M. Malinconico, A. Buzarovska, A. Grozdanov, G. Gentile, M.E. Errico. 2007. “Natural Fiber Eco-Composites, Polym.” *Polymer composites*: 98–107.

Haque, Mominul et al. 2010. “Physicomechanical Properties of Chemically Treated Palm Fiber Reinforced Polypropylene Composites.” *Journal of Reinforced Plastics and Composites* 29(11): 1734–42.

Huang, Bo Tao et al. 2018. “Fatigue Deformation Behavior and Fiber Failure Mechanism of Ultra-High Toughness Cementitious Composites in Compression.” *Materials and Design* 157: 457–68.

Kim, Dong joo, Antoine E. Naaman, and Sherif El-Tawil. 2008. “Comparative Flexural Behavior of Four Fiber Reinforced Cementitious Composites.” *Cement and Concrete Composites* 30(10): 917–28.

Li, Qing Hua, Bo Tao Huang, and Shi Lang Xu. 2016. “Development of Assembled Permanent Formwork Using Ultra High Toughness Cementitious Composites.” *Advances in Structural Engineering* 19(7): 1142–52.

Li, V.C. 2008. Concrete Construction Engineering Handbook *Concrete Construction Engineering Handbook*. CRC Press.

Li, Weixin et al. 2017. “A Multiscale Framework for the Simulation of the Anisotropic Mechanical Behavior of Shale.” *International Journal for Numerical and Analytical Methods in Geomechanics* 41(14): 1494–1522.

Li, Zhijian, Lijing Wang, and Xungai Wang. 2004. “Compressive and Flexural Properties of Hemp Fiber Reinforced Concrete.” *Fibers and Polymers* 5(3): 187–97.

Lifshitz Sherzer, G., E. Schlangen, G. Ye, and A. E. Gal. 2020. “Evaluating Compressive Mechanical LDPM Parameters Based on an Upscaled Multiscale Approach.” *Construction and Building Materials* 251.

Luo, Wen, Viet T. Chau, and Zdeněk P. Bažant. 2019. “Effect of High-Rate Dynamic Comminution on Penetration of Projectiles of Various Velocities and Impact Angles into Concrete.” *International Journal of Fracture* 216(2): 211–21.

Ma, Hui et al. 2015. “Tailoring Engineered Cementitious Composites with Local Ingredients.” *Construction and Building Materials* 101(Part 1): 584–95.

Matheu, P. S., K. Ellis, and B. Varela. 2015. “Comparing the Environmental Impacts of Alkali Activated Mortar and Traditional Portland Cement Mortar Using Life Cycle Assessment.” *IOP Conference Series: Materials Science and Engineering* 96(1).

Munawar, Sasa Sofyan, Kenji Umemura, and Shuichi Kawai. 2007. “Characterization of the Morphological, Physical, and Mechanical Properties of Seven Nonwood Plant Fiber Bundles.” *Journal of Wood Science* 53(2): 108–13.

Patel, R, and V R Patel. 2018. “Using Jute Fiber in Cement Concrete Pavement with IRC Mix Design and Ambuja Mix Design.” ... *Journal of Engineering and Technology (IRJET ...*: 1092–95. https://www.researchgate.net/profile/Prof-Patel-2/publication/332189771_IRJET-V5I2235/links/5ca5e8fb92851c64bd4e5935/IRJET-V5I2235.pdf.

Qin, Fengjiang et al. 2020. “Use of High Strength, High Ductility Engineered Cementitious Composites (ECC) to Enhance the Flexural Performance of Reinforced Concrete Beams.” *Journal of Building Engineering* 32.

Saba, N., M. T. Paridah, and M. Jawaid. 2015. “Mechanical Properties of Kenaf Fibre Reinforced Polymer Composite: A Review.” *Construction and Building Materials* 76: 87–96.

Satyanarayana, K. G. et al. 1990. “Natural Fibre-Polymer Composites.” *Cement and Concrete Composites* 12(2): 117–36.

Satyanarayana, K. G., A. G. Kulkarni, and P. K. Rohatgi. 1981. “Potential of Natural Fibres as a Resource for Industrial Materials in Kerala.”

Wei, Jianqiang, and Christian Meyer. 2015. “Degradation Mechanisms of Natural Fiber in the Matrix of Cement Composites.” *Cement and Concrete Research* 73: 1–16.

Williams, George I., and Richard P. Wool. 2000. “Composites from Natural Fibers and Soy Oil Resins.” *Applied Composite Materials* 7(5–6): 421–32.

Yan, Libo, Nawawi Chouw, and Krishnan Jayaraman. 2014. “Flax Fibre and Its Composites - A Review.” *Composites Part B: Engineering* 56: 296–317.

Yang, En Hua, Shuxin Wang, Yingzi Yang, and Victor C. Li. 2008. “Fiber-Bridging Constitutive Law of Engineered Cementitious Composites.” *Journal of Advanced Concrete Technology* 6(1): 181–93.

Yang, Enhua, and Victor C. Li. 2005. “Rate Dependence in Engineered Cementitious Composites.” *International RILEM Workshop on High Performance Fiber Reinforced Cementitious Composites in Structural Applications* (1): 83–92. http://www.advancedmaterialscouncil.org/prepare/uploaded_docs/material_id_387_pub/EYang-Rate.pdf.

Yu, Ke Quan et al. 2018. “Development of Ultra-High Performance Engineered Cementitious Composites Using Polyethylene (PE) Fibers.” *Construction and Building Materials* 158: 217–27.