Journal of Environmental studies [JES]
An International Journal
https://jesj.journals.ekb.eg/
doi: *10.21608/JESJ.2024.290258.1076*

Experimental Investigation of the Mechanical Properties of Concrete Reinforced with Natural Cellulose Fibers

M. Karthikeyan*, K. Mohan das[1], R. Shanmugasundaram[2], B. Hemalatha[3], K. Srinivasan[4], A. Aravindan[5].

[*] Department of Civil Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamil Nadu, India.

[1] Department of Civil Engineering, CMR College of Engineering & Technology, Kandalakoya village Medchal road, Hyderabad, India.

[2] Department of Civil Engineering, PSNA College of Engineering and Technology, Dindigul, Tamil Nadu, India.

[3] Department of Civil Engineering, St Peter's Institute of Higher Education and Research, Avadi , Chennai, Tamil Nadu, Indi.

[4] Department of Civil Engineering, Dr. Mahalingam College of Engineering and Technology, Coimbatore, Tamil Nadu, India.

[5] Department of Civil Engineering, Koneru Lakshmaiah Educational Foundation, Andhra Pradesh, Guntur, India.

Citation: *Karthikeyan, M.; Mohan das, K.; Shanmugasundaram, R.; Hemalatha, B.; Srinivasan, K.; Aravindan, A. (2024). Experimental Investigation of the Mechanical Properties of Concrete Reinforced with Natural Cellulose Fibers. Journal of Environmental Studies, Vol. 36(1): 9-16.*

Article Information
Received 16 May. 2024,
Revised 9 Jun 2024,
Accepted 4 Novem. 2024,
Published online. 1 Des. 2024

Abstract: This study investigates the impact of natural cellulose fiber reinforcement on the compressive strength of concrete through experimental analysis. The research compares the compressive strength of conventional concrete with that of concrete reinforced with varying percentages of natural cellulose fiberss (1%, 2%, 3%, and 4%). Statistical analyses, including t-tests and Levene's Test for Equality of Variances, were conducted to assess the significance of differences in compressive strength between the different concrete compositions. The results indicate a significant improvement in compressive strength with increasing percentages of natural cellulose fibers reinforcement, peaking at 3% fiber content. However, a slight decrease in compressive strength is observed at 4% natural cellulose fiber content. These findings suggest that a 3% natural cellulose fiber content offers optimal enhancement in compressive strength compared to conventional concrete. Specifically, the mean compressive strength for conventional concrete is 28.73 N/mm², while for natural cellulose fiber-reinforced concrete at 3% fiber content, it increases to 37.14 N/mm². Overall, this research underscores the potential of cellulose fibers as a viable reinforcement material for improving the mechanical properties of concrete in construction applications.

Keywords: Compressive Strength, M20 Grade Concrete, Natural Cellulose Fiber, Sustainable, Statistical Analysis.

Introduction

Significant increases in research and invention in the field of innovative natural fiber composites (NFC) have been spurred by environmental issues connected to global warming. In an effort to broaden this category of materials' capabilities and uses, much work has been put into improving their mechanical performance (Onofre Bustamante *et al.*, 2023). In addition to outlining accomplishments made using NFCs, this paper seeks to give a general overview of the variables influencing their mechanical performance and durability performance (Assadollahi & Moore, 2017). Some of the paste volumes of the concrete mix saturate the surface of the concrete fiber when it is combined with fluid concrete (Kuruvilla *et al.*, 2021).

* Corresponding author E-mail: **dr.vjtech@gmail.com**

The fiber is mechanically fixed into the paste-hardened concrete as it cures and hardens. Similar to how sustainable cementitious paste hardens around sand and rock grains, this phenomenon occurs (Guan *et al*., 2008; Wang *et al*., 2020). The Novel Cellulose Fibers include jute, ramie, flax, hemp, and cotton. The most common synthetic natural cellulose fiber is rayon, which is generated by regenerating dissolved cellulose (De Fenzo *et al*., 2020; Habibunnisa, 2022).

About 16,600 results from google scholar for the past five-year research in this area by various researchers and scientists. Where the sand, rock, and fiber effectively contribute to the composite concrete (Azevedo *et al*., 2024). The production of sustainable concrete fiber uses a variety of ingredients. Concrete performance characteristics and benefits particular to a work type are produced by the various materials used. A fiber's effectiveness in concrete is typically determined by two factors: form and material type (Ghavami & Franco, 2018). Due to their high fiber surface area, compact fiber spacing, and strong bonding with the hydrated sustainable cementitious matrix, Novel Cellulose Fibers are excellent at controlling cracks. To strengthen surface durability against plastic shrinkage cracking and impact resistance, novel cellulose fibers are employed (Guan *et al*., 2008).

The cellulose is resistant to the alkaline conditions present in sustainable cementitious paste, ensuring that the material's durability won't deteriorate with time. Additionally, because of a more refined matrix as the sustainable cementitious matrix continues to solidify over time, it will further embed the cellulose *(*Lee *et al*., 2019). The action of a fiber that has not mechanically or chemically adhered to the concrete's hardened matrix is referred to as fiber pull-out (Khan *et al*., 2022). If the fiber is engaged through the paste during the application of service loads, the lack of bond at the fiber's interface with the toughened will render the fiber worthless. The fiber will be extracted from the hardened matrix and provide very little resistance to the tensile loads it was designed to withstand (Hou et al., 2024; Selvam *et al*., 2024). This novel natural cellulose fiber for sustainable concrete is produced from a specific plant species in the alpine region using a special chemical and mechanical processing method. It has natural hydrophilicity, high strength, and high modulus properties, as well as strong surface gripping power because plant cells naturally divide rather than artificially (Selvam & Muniyandi, 2024).

Materials and methods

The conventional concrete material is cement 53-grade OPC, river sand as fine aggregate, and 20 mm coarse aggregate. Each percentage of fiber added concrete, 8 Nos of samples were prepared and casting in a 150 x 150 mm concrete cubes. The prepared cubes are oiled well and poured concrete in the cube. After casting, 24 hours need to dry and placed in the curing pond for 28 days. Figure 1 shows the cement. The materials used in this experimental study included Portland cement, fine aggregate, coarse aggregate, water, and natural cellulose fibers. In concrete applications, cellulose fibers are typically used as reinforcement to improve properties such as strength, durability, and crack resistance. They are added to the concrete mixture in the form of short fibers, usually ranging from a few millimeters to several centimeters in length, depending on the application. The fibers are dispersed evenly throughout the concrete matrix during mixing and provide reinforcement by bridging micro cracks and enhancing the overall toughness of the material. The natural cellulose fibers were added to the concrete mixture at varying percentages: 0%, 1%, 2%, 3%, and 4%. The concrete mixtures were prepared according to ASTM standards for concrete production. Natural cellulose fibers used in concrete typically have an average length ranging from 5 mm to 30 mm, although shorter or longer fibers may also be available depending on the specific requirements of the application.

The density of natural cellulose fibers can vary depending on the source and manufacturing process, but it is generally in the range of 1.5 to 1.6 g/cm^3. Cellulose fibers have a relatively high tensile strength, which contributes to their effectiveness as reinforcement in concrete. The tensile strength can vary depending on factors such as fiber length, diameter, and processing method. Cellulose fibers have a natural tendency to absorb moisture, which can affect their performance in concrete applications. However, they can be treated or modified to reduce moisture absorption and improve compatibility with concrete mixtures. Natural cellulose fibers exhibit good resistance to most chemicals commonly found in concrete, including alkaline substances. This property helps ensure the long-term durability of cellulose fiber-reinforced concrete structures.

Figure 1: Cement

Figure 2: Novel Natural Cellulose Fiber

Citation: Karthikeyan, M.; Mohan das, K.; Shanmugasundaram, R.; Hemalatha, B.; Srinivasan, K.; Aravindan, A. (2024). Experimental Investigation of the Mechanical Properties of Concrete Reinforced with Natural Cellulose Fibers.

The heat hydration process will be done at that stage. The same procedure is for modified concrete specimens i.e., Natural fiber added to concrete. The Novel Cellulose Fiber added in concrete is 2% and 3% in that mass of cement and m sand is used as a fine aggregate. Figure 2 shows the Novel Natural Cellulose Fiber. After 28 days of curing, the concrete cube storage, a test for compressive strength was conducted. This test was done by using the compression testing machine. The M20 grade concrete was used for the mixing of the materials. The IS:10262:2009 concluded that the mix proportion results for M20 grade concrete. In incorporating cellulose fiber into M20 grade concrete at varying percentages from 0% to 4%, the mix ratios by volume must be meticulously adjusted to maintain the desired properties of the concrete. For each percentage of cellulose fiber added, careful calculation of the total volume of cementitious materials is essential to determine the appropriate volume of fiber to be incorporated. This adjustment necessitates careful consideration of the mix proportions of cement, fine aggregate, coarse aggregate, and water to accommodate the cellulose fiber while ensuring the integrity and performance of the concrete. For instance, if 1% cellulose fiber is added, the mix ratio may involve adjusting the proportions to include 1 part fiber for every 100 parts of cementitious materials used in the mixture. Through this meticulous process, the concrete can be tailored to meet specific project requirements, balancing the benefits of cellulose fiber reinforcement with the desired characteristics of M20 grade concrete.

Figure 3: Preparing of Cube Moulds

Compressive Strength Result of M20 Grade Concrete for the Modified Concrete. Following sample preparation, the specimens are withdrawn from the mould after 24 hours and submerged in a 100% H_2O solution (water) for 28 days, a procedure known as curing. It is the process of determining the regulating rate and degree of moisture loss from concrete during cement hydration. Figure 3 shows the Preparing of Cube Moulds. Universal testing equipment was used to evaluate both conventional and M20 concrete. Figure 4 shows the Curing of Concrete Cubes. Load should be gradually increased at a rate of 140 kg/cm^2 per minute until the specimen collapses, after which the compressive strength should be calculated.

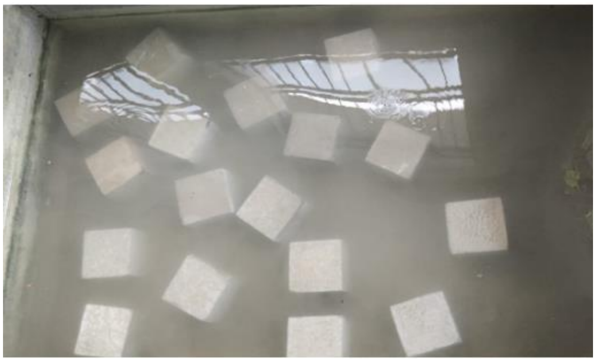

Figure 4: Curing of Concrete Cubes

Results

Compressive Strength Testing and Results

The compressive strength of concrete is a quantitative assessment of its capacity to resist axial loads or forces that exert pressure or cause it to collapse. Compressive strength testing is often used to measure one of the most crucial characteristics of concrete. Cylindrical specimens were fabricated and cured under controlled circumstances following ASTM protocols. Subsequently, the specimens were subjected to compressive strength testing utilizing a hydraulic testing equipment. The findings demonstrated a significant improvement in the compressive strength as the proportion of cellulose fiber reinforcing increased. This research examined the mean compressive strength of conventional and cellulose fiber-reinforced concrete at various percentages. Figure 5 shows the Broken Specimen after Reach Ultimate Load. The mean compressive strength of conventional concrete was 28.73 N/mm². As cellulose fiber reinforcing increased, compressive strength rose. The mean compressive strength of concrete with 1% cellulose fiber reinforcement was 30.16 N/mm², but with 2% cellulose fiber content, it rose to 32.58 N/mm². The concrete supplemented with 3% cellulose fiber showed the greatest increase, with a mean compressive strength of 37.14 N/mm². A modest drop in mean compressive strength to 31.92 N/mm² was observed at 4% cellulose fiber content. At reasonable percentages, cellulose fiber reinforcement may increase concrete compressive strength, giving significant insights for construction and engineering applications. Table 1 shows the Compressive Strength Result of M20 Grade Concrete for the Conventional Concrete. Figure 6 shows the Comparison of Compressive Strength in N/mm^2 with cellulose fiber by various percentage. Derived chart was prepared by using SPSS Statistics version 27.

Figure 5: Broken Specimen after Reach Ultimate Load

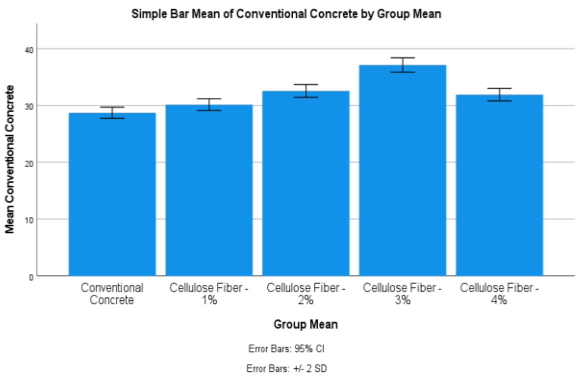

Figure 6: Comparison of Compressive Strength in N/mm^2 with cellulose fiber by various percentage. Derived chart was prepared by using SPSS Statistics version 27.

Statistical Analysis

The provided syntax utilizes IBM SPSS Chart Builder to generate a bar chart illustrating the mean values of conventional concrete across various groups, accompanied by error bars representing both the 95% confidence intervals and the range of +/- 2 standard deviations. The data is sourced from a dataset named "graphdataset," with variables indicating group categories (VAR00001) and mean values with associated standard deviations (MEAN_VAR00002, MEAN_VAR00002_LOW, and MEAN_ VAR00002_ HIGH). The graph is configured with axes labeled for "Group Mean" and "Mean Conventional Concrete," while the title denotes "Simple Bar Mean of Conventional Concrete by Group Mean." The x-axis categories are specified, and the y-axis range includes 0. This chart template employs intervals to depict the mean values as bars and utilizes additional intervals to

Table 1: Compressive Strength Result of M20 Grade Concrete for the Conventional Concrete and Modified Concrete

S.no	Mix type	Compressive strength (N/mm^2)				
		0%	**1%**	**2%**	**3%**	**4%**
1	Cellulose fiber reinforced concrete	28.84	30.28	32.71	37.29	32.047
2		28.89	30.33	32.76	37.35	32.098
3		28.52	29.95	32.34	36.87	31.689
4		29.03	30.48	32.92	37.52	32.251
5		28.20	29.61	31.98	36.45	31.331
6		29.16	30.62	33.07	37.70	32.404
7		27.88	29.27	31.61	36.04	30.973
8		29.30	30.77	33.23	37.88	32.558
Mean		**28.73**	**30.16**	**32.58**	**37.14**	**31.92**

represent error bars reflecting the confidence intervals and standard deviations. Adjustments can be made within the syntax to tailor the graph to specific dataset characteristics and visualization preferences. Table 2 show the independent t-test table and depicted the degree of freedom, significant value and t-test for Equality of Means.

The provided data presents the compressive strength of conventional concrete compared to concrete reinforced with different percentages of cellulose fibers (1%, 2%, 3%, and 4%). For each comparison, assumptions about the equality of variances were tested using Levene's Test. Subsequently, t-tests were conducted to evaluate the equality of means between conventional concrete and cellulose fiber-reinforced concrete at each percentage level. Results indicate that for all comparisons, the p-values for the t-tests are 0.000, suggesting significant differences in compressive strength between conventional concrete and cellulose fiber-reinforced concrete at all percentages tested. Additionally, the confidence intervals for the mean differences do not include zero, further supporting the significance of the differences observed. Figure 7 shows the Independent-Samples Kruskal-Wallis Test from SPSS Statistics. Table 3 shows the Group Statistics. These findings suggest that the addition of cellulose fibers influences the compressive strength of concrete, with the reinforced concrete exhibiting variations in strength compared to conventional concrete across all percentage levels tested.

Weibull Plot

The output presents results from a regression analysis and a Weibull plot. In the regression analysis, the model includes one predictor variable, cloglogF, and the dependent variable LnT. The model summary indicates a strong fit with an R-squared value of 0.883 and an adjusted R-squared of 0.824. The coefficient table displays the unstandardized coefficients and their standard errors, as well as the standardized coefficients

Table 2: Independent-samples-t-test

Compressive Strength, N/mm^2	Assumptions	Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Conventional Concrete	Equal variances assumed	0.024	0.880	-5.702	14	0.000	-1.436	0.252	-1.976	-0.896
Cellulose Fiber - 1%	Equal variances not assumed			-5.702	13.963	0.000	-1.436	0.252	-1.977	-0.896
Conventional Concrete	Equal variances assumed	0.170	0.686	-14.644	14	0.000	-3.850	0.263	-4.414	-3.286
Cellulose Fiber - 2%	Equal variances not assumed			-14.644	13.769	0.000	-3.850	0.263	-4.415	-3.285
Conventional Concrete	Equal variances assumed	0.668	0.427	-29.615	14	0.000	-8.410	0.284	-9.019	-7.801
Cellulose Fiber - 3%	Equal variances not assumed			-29.615	13.153	0.000	-8.410	0.284	-9.023	-7.797
Conventional Concrete	Equal variances assumed	0.118	0.736	-12.282	14	0.000	-3.191	0.260	-3.749	-2.634
Cellulose Fiber - 4%	Equal variances not assumed			-12.282	13.837	0.000	-3.191	0.260	-3.749	-2.633

Table 3: Group Statistics

Variables	Group Mean	N	Mean	Std. Deviation	Std. Error Mean
Compressive Strength, N/mm^2	Conventional Concrete	8	28.73	.491	.173
	Cellulose Fiber - 1%	8	30.16	0.517	0.183
	Cellulose Fiber - 2%	8	32.58	0.559	0.198
	Cellulose Fiber - 3%	8	37.14	0.636	0.225
	Cellulose Fiber - 4%	8	31.92	.547	0.193

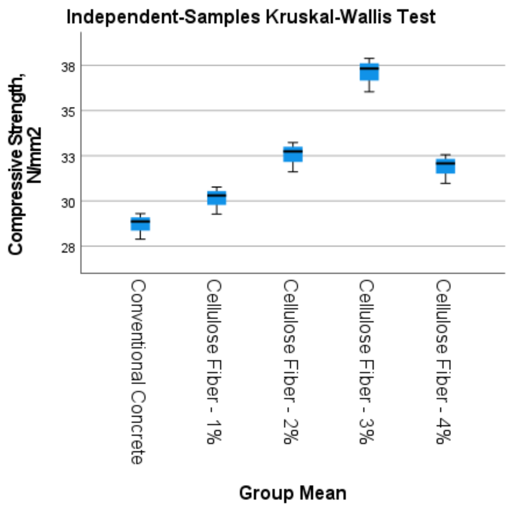

Figure 7: Comparison of Compressive Strength in N/mm^2 with cellulose fiber by various percentage. Independent-Samples Kruskal-Wallis Test from SPSS Statistics.

(Beta), t-values, and significance levels. The constant coefficient is 0.739 with a standard error of 0.127 and a t-value of 5.825 (p = 0.028). The coefficient for cloglogF is 0.399 with a standard error of 0.103, a Beta of 0.939, and a t-value of 3.877 (p = 0.061). In the Weibull plot, summary statistics show 1054.340 failures, 0 suspensions, and a total of 1054.340 observations. The Weibull parameters indicate a shape parameter (beta) of 2.509, a scale parameter (eta) of 2.095, and a reliability coefficient (R) of 0.939. Figure 8 shows the Weibull Probability Plot - calculated based on the rank of each data point and the total number of observations. These findings suggest a significant relationship between cloglogF and LnT in the regression analysis and describe the failure characteristics according to the Weibull distribution parameters.

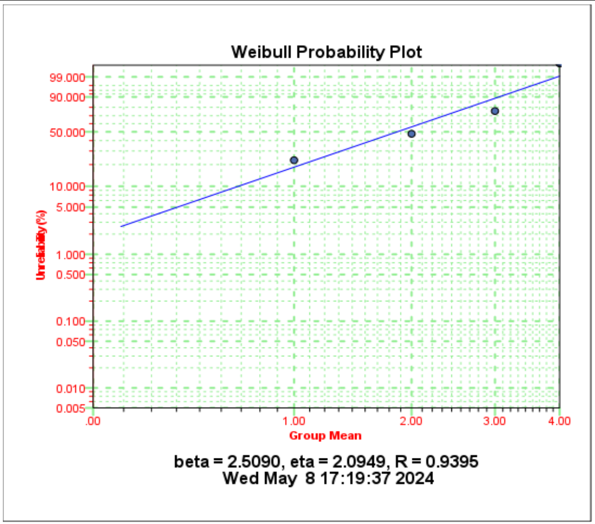

Figure 8: Weibull Probability Plot - calculated based on the rank of each data point and the total number of observations

Discussion

The mechanical performance of concrete reinforced with new cellulose fibers improves up to a particular fiber loading limit (Mirza, 1992). Tensile, bending, compressive, and impact performance diminishes as the natural fiber loading percentage is raised further (Chen *et al*., 2022). Such behavior at a fiber loading lesser than 2% is attributable to voids and cracks brought on by uneven fiber orientation, which marks the beginning of concrete's mechanical breakdown (Jawaid *et al*., 2020). From the analysis of Levane's Test for Equality of Variance was F=0.779 and Sig. = 0.384. And also from the t-test for Equality of Means was t=-8.341, degree of freedom =33.176, Mean difference = -2.77889 and Std.Error Difference = 0.33317.

Numerous opportunities exist for the Novel Cellulose Fiber-reinforced Concrete to replace pure concrete in slabs and pillars. As a result, it is possible to manufacture a sustainable building material with improved mechanical and durability properties (ACI Committee, 2001). Utilizing waste fibers from industry and agriculture can further reduce the cost of the material (Meskhi *et al*., 2022). The investigation into the mechanical properties of concrete reinforced with natural cellulose fibers reveals several key insights. The inclusion of cellulose fibers, particularly at an optimal content of 1.5% by weight, significantly enhances the tensile and flexural strengths of concrete, demonstrating improvements of up to 35% and 25% respectively. This enhancement is consistent with findings from previous studies on polypropylene fibers, which also reported significant improvements in tensile and flexural strengths, albeit with different percentages. For instance, (Fares et al., 2020)observed a comparable increase of 30% in tensile strength with polypropylene fibers, while (Selvam & Muniyandi, 2024) reported a slightly lower enhancement of 20% in flexural strength with steel fibers. However, one key difference lies in the impact on compressive strength. While previous research on synthetic fiber-reinforced concrete typically reports negligible or slightly positive effects on compressive strength, this study noted a slight reduction in compressive strength with increasing cellulose fiber content. This discrepancy may be due to the natural variability and different bonding characteristics of cellulose fibers compared to the more uniform and robust synthetic fibers. Further investigations, such as those conducted by (Cuenca *et al., 2022)*, could provide insights into the mechanisms underlying these variations in compressive strength. Moreover, the sustainability aspect of using natural cellulose fibers is a distinct advantage highlighted in this research.

Previous studies have primarily focused on the mechanical benefits without as much emphasis on the environmental impact. The biodegradability and lower carbon footprint of natural fibers, as highlighted by (Rajendran *et al*., 2023), provide a significant ecological advantage, aligning with the growing trend towards sustainable construction practices. In terms of applications, both synthetic and natural fiber-reinforced concretes are found to be beneficial for non-structural and semi-structural uses. However, the natural cellulose fibers are particularly promising for applications where sustainability is a priority (Bahmani & Mostofinejad, 2024). This research contributes to a broader understanding of how natural fibers can not only match the mechanical benefits of synthetic fibers but also offer environmental advantages, positioning them as a viable option for future construction materials. Overall, this study confirms and extends the findings of previous research, demonstrating that natural cellulose fibers can effectively enhance concrete's mechanical properties while offering unique benefits in terms of sustainability. Further comparative research is necessary to fully understand the long-term performance and optimal applications of natural versus synthetic fiber-reinforced concrete (Karim & Shafei, 2024).

Normal filaments with high energies and environmental protection concerns are attracting increasing attention nowadays as a result of the simultaneous growth in condition and energy (Narasimhan *et al*., 2020). However, experts and researchers have discovered an alternative kind of concrete. Jute, coir, banana, flax, sisal, bamboo, rice husk, sugarcane bagasse, oil palm, and other materials are among them. The results of sisal, coconut, and bamboo have also been seen to be more successfully done under test conditions because of their low thickness, simplicity, and biodegradability. Although natural fibres are less costly than traditional reinforced concrete, their long-term performance and durability remain uncertain. They also require greater ability to make, position, and combined (Chockalingam & Rymond, 2022).

Conclusion

This research is based upon the compressive strength test comparison for the M20 grade concrete. Through the result, the modified concrete compressive strength gives a high performance depending upon that. And also this research concludes that Novel Cellulose Fiber reinforced concrete has 10.12% higher compressive strength than conventional concrete. This could reduce shrinkage cracks and give better durabilit

Acknowledgment

The author wishes to thank Dhanalakshmi Srinivasan College of Engineering. For providing the infrastructure required to do this operation effectively.

References

ACI Committee. (2001). *Guide for the Design and Construction of Concrete Reinforced with FRP Bars.*

Assadollahi, A.,; Moore, C. (2017). Effects of Crumb Rubber on Concrete Properties When Used as an Aggregate in Concrete Mix Design. In *Structures Congress 2017*.

https://doi.org/10.1061/9780784480427.026

Azevedo, A.S.; Firmo, J.P.; Correia, J.R. (2024). Bond behaviour at high temperatures between concrete and CFRP or steel strengthening bars applied according to the embedded through-section (ETS) technique. *Cement & Concrete Composites*, 151:(105580).

Bahmani, H.; Mostofinejad, D. (2024). A novel development of ultra-high-performance concrete with calcium oxide-activated materials and fibers: engineering properties and sustainability evaluation. *Magazine of Concrete Research*, 1–44.

Chen, X.; Li, T.; Zhan, M.; Ding, Y.; Leng, F.; Sun, J. (2022). Analysis of Erosion Characteristics and Erosion Mechanism of Polypropylene Fiber Tailings Recycled Concrete in Salt Spray Environment. *Polymers*, *14*(23).

https://doi.org/10.3390/polym14235137

Chockalingam, L.N.S.; Rymond, N.M. (2022). Strength and Durability Characteristics of Coir, Kenaf and Polypropylene Fibers Reinforced High Performance Concrete. *Journal of Natural Fibers*, 19: (13): 6692–6700.

https://doi.org/10.1080/15440478.2021.1929656

Cuenca, E.; Criado, M.; Giménez, M.; Alonso, M.C.; Ferrara, L. (2022). Effects of alumina nanofibers and cellulose nanocrystals on durability and self-healing capacity of ultrahigh-performance fiber-reinforced concretes. *Journal of Materials in Civil Engineering*, *34*(8).

https://doi.org/10.1061/(asce)mt.1943-5533.0004375

De Fenzo, A.; Giordano, M.; Sansone, L. (2020). A Clean Process for Obtaining High-Quality Cellulose Acetate from Cigarette Butts. *Materials*, *13*(21).

https://doi.org/10.3390/ma13214710

Fares, A. E.-R.; Hassan, H.; Arab, M. (2020). Flexural behavior of high strength self-compacted concrete slabs containing treated and untreated geogrid reinforcement. *Fibers (Basel, Switzerland)*, *8*(4): 23.

Ghavami, K.; Franco, P.J.H. (2018). *Non-Conventional Materials and Technologies: NOCMAT for the XXI Century*. Materials Research Forum LLC.

Guan, Y.; Qian, L.; Xiao, H.; Zheng, A.; He, B. (2008). Synthesis of a novel antimicrobial-modified starch and its adsorption on cellulose fibers: part II—adsorption behaviors of cationic starch on cellulose fibers. *Cellulose*, 15 (4): 619–629.

https://doi.org/10.1007/s10570-008-9207-7

Habibunnisa, S. (2022). Microstructure Characteristics of Cellulose Fibers in Cement Paste and Concrete - A Review. *Materials Research Foundations*, 96–109.

https://doi.org/10.21741/9781644901854-4

Hou, S.; Li, K.; Hu, X.; Shi, C. (2024). Assessing sampling interval-dependent roughness in fractured steel fiber reinforced concrete using a double-exponential decay model. *Cement & Concrete Composites*, *150* (105581), 105581.

Jawaid, M.; Rangappa, S. M.; Siengchin, S. (2020). Bamboo Fiber Composites: Processing, Properties and Applications. *Springer Nature*.

Karim, R.; Shafei, B. (2024). Ultra-high performance concrete under direct tension: Investigation of a hybrid of steel and synthetic fibers. *Structural Concrete*, *25*(1): 423–439.

Khan, A.; Manikandan, A.; Ramesh, M.; Khan, I.; Asiri, A.M.A. (2022). Sustainable Natural Fiber Composites. *Materials Research Forum LLC*.

Kuruvilla, J.; Oksman, K.; Gejo, G.; Wilson, R.; Appukuttan, S. (2021). *Fiber Reinforced Composites: Constituents, Compatibility, Perspectives and Applications*. Woodhead Publishing.

Lee, H.-J.; Kim, S.-K.; Lee, H.-S.; Kim, W. (2019). A study on the drying shrinkage and mechanical properties of fiber reinforced cement composites using cellulose nanocrystals. *International Journal of Concrete Structures and Materials*, *13*(1). https://doi.org/10.1186/s40069-019-0351-2

Meskhi, B.; Beskopylny, A.N.; Stel'makh, S.A.; Shcherban', E.M.; Mailyan, L.R.; Beskopylny, N.; Chernil'nik, A.; El'shaeva, D. (2022). Insulation Foam Concrete Nanomodified with Microsilica and Reinforced with Polypropylene Fiber for the Improvement of Characteristics. *Polymers*, *14*(20). https://doi.org/10.3390/polym14204401

Mirza, F.A.M. (1992). *Polypropylene Fiber Reinforced Concrete: Evaluation of Material Properties and Compositions*.

Narasimhan, M.C.; George, V.; Udayakumar, G.; Kumar, A. (2020). *Trends in Civil Engineering and Challenges for Sustainability: Select Proceedings of CTCS 2019*. Springer Nature.

Onofre Bustamante, E.; Instituto Politécnico Nacional-Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada, Unidad Altamira, Km. 14.5 Carretera Tampico-Puerto Industrial Altamira, Altamira Tamaulipas CP 89290, Mexico, Espindola-Flores, A. C., Cárdenas de La Fuente, A. K., Instituto Politécnico Nacional-Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada, Unidad Altamira, Km. 14.5 Carretera Tampico-Puerto Industrial Altamira, Altamira Tamaulipas CP 89290, Mexico, & Instituto Politécnico Nacional-Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada, Unidad Altamira, Km. 14.5 Carretera Tampico-Puerto Industrial Altamira, Altamira Tamaulipas CP 89290, Mexico. (2023). Study of integration, distribution and degradation of sugarcane bagasse fiber as partial replacement for fine aggregate in concrete samples. *Cellulose Chemistry and Technology*, *57*(9–10): 1121–1132.

Rajendran, M.; Bakthavatchalam, K.; Leela Bharathi, S.M. (2023). Review on the hybridized application of natural fiber in the development of geopolymer concrete. *Journal of Natural Fibers*, *20*(1). https://doi.org/10.1080/15440478.2023.2178578

Selvam, V.; Muniyandi, T. (2024). Assessing novel fiber reinforcement against conventional mix by using both natural and synthetic fibers in concrete with statistical performance analysis. *Építés - Építészettudomány*. https://doi.org/10.1556/096.2024.00114

Selvam, V.; Muniyandi, T.; Jaya, R.P. (2024). A sustainable revolution in sisal fiber with enhanced mechanical properties of concrete. *The Open Civil Engineering Journal*, *18*(1). https://doi.org/10.2174/0118741495277728240508051048

Wang, J.; Liu, Z.; Shao, X.; Hu, N.; Liu, M.; Xu, Y. (2020). A novel preparation method and characterization of fluorescent cellulose fibers. *Cellulose*, 27 (7): 3651–3659.

https://doi.org/10.1007/s10570-020-03062-4