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Sustainable Strengthening of Concrete Using Lathe Waste Steel Fibers: Experimental and FEA Analysis

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Abstract. The construction industry is growing fast and increasing the demand for concrete which requires sustainable materials. Concrete is weak in tension and needs fiber reinforcement to improve strength. This study explores lathe waste steel fibers as a sustainable option to enhance tensile properties. Local industries produce large amounts of lathe waste that can be used in fiber-reinforced concrete. Traditional destructive testing is expensive and slow because it needs heavy machinery like Universal Testing Machines. This research combines destructive and computational analysis using ANSYS 15 for finite element modeling. Cylindrical and beam specimens were tested with fiber ratios from 0 to 3 percent. Results show that 2.5 percent fiber content gives the best compressive and flexural strength. Scanning electron microscopy confirms stronger bonding as fibers break within the matrix instead of pulling out. This study proves lathe waste steel fibers improve both performance and sustainability in construction.

Keywords: sustainable construction, fiber reinforced concrete, lathe waste steel fibers, finite element analysis, ANSYS 15 workbench, non destructive testing, computational analysis, scanning electron microscopy.

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1. Introduction

In 1950, 200 million tons of cement were consumed, but in 2006, 21–31 billion tons of concrete [2.54 billion tons of cement] were consumed globally [1, 2]. About 2.80 million tons were used in concrete for mega projects like motorways, dams, mass transit, and more [3] . With growing environmental awareness, developing countries are increasingly focused on conserving natural resources, reducing material costs, and recycling waste, aligning with the global trend of sustainable construction. Many developing countries must work to save natural resources, reduce material costs, and recycle waste [4].

Recycling industrial waste protects the environment and boosts the economy. The importance of recycling industrial waste lies in its potential to not only protect the environment but also support economic stability in resource-limited regions [5]. In the rapidly growing construction sector, the demand for durable infrastructural provision demands for concrete mechanical strength testing [6]. However, most of the testing methods utilized in this process, which are considered destructive, present environmental, economic, and ethical challenges [7]. Concrete waste associated with these procedures is particularly destructing to the environment [8]. Unlike several construction materials, concrete is not recyclable or easily marketed due to its adverse environmental elements which presents an urgent need for alternatives in both material use and testing practices [9]. This increases the already carbon footprint in the industry and provides sufficient reason for alternative methods of testing [10].

Destructive testing procedures involve critical and repetitive procedures that take time and end-user considerations [11]. This method relies on heavy machinery that crushes the materials used in the test [12]. Construction firms have to acquire universal testing machines for the test; this increases testing companies' budgets significantly. Financial and Access Challenges the procedure is expensive, making it impossible for small construction companies to afford both the material and human resource needed to test their materials. Most companies are unable to purchase universal testing machine needed for the test [13]. To address these accessibility and sustainability challenges, this research explores a cost-effective, sustainable alternative through computational analysis, minimizing the environmental footprint associated with destructive testing.

The need to create sustainable and affordable there is a significant need to develop cost-effective and sustainable alternative methods for destructive testing [13]-[7]. Currently, the carbon-related issues generated by concrete waste as well as the economic barriers surrounding the testing process are negatively affecting the accessibility of the process [14]. Non-destructive testing becomes an integral process for the future of construction [15].

Fiber-reinforced concrete [FRC] is sand, gravel, water, and short fibers [steel, glass, synthetic, asbestos, carbon, organic, and natural] that strengthen concrete [16, 17]. Different fiber geometries, materials, delamination, direction, and densities are used in reinforced concrete structures [18]. Fiber-reinforced concrete is uneconomical because steel and other fibers are expensive [19]. Today, waste management must focus on industrial waste utilization. Experimental studies on lathe scrap reinforced concrete showed a significant increase in compressive strength compared to plain cement concrete. Addressing this issue, recent studies have shown the potential of using industrial waste such as lathe scrap as an alternative fiber for reinforcement [20]. Additionally, flexural strength increased significantly [20]. Lathe scrap, which resembles steel fiber, can be used to make Fiber-reinforced concrete [17]-[21] .

This research aims to fill the gap by investigating the use of lathe waste steel fibers in fiber-reinforced concrete to improve its mechanical properties in a sustainable way. Using Finite Element Analysis (FEA). Finite Element Analysis [FEA] predicts component responses to structural loads for structure evaluation [22-25]. Since it is faster and cheaper than experimental methods, FEA is preferred for studying concrete behavior [26]. Experimental and FEA analyses were conducted on three SFRC beams [250×350×2000 mm] with 30 kg/m3 steel fibers [27]. Commercial software ANSYS is used for FEA analysis, with elements for concrete and elements for steel fibers [28].

The aim of this research was to computational analysis for the mechanical properties [compressive and flexural strength] of concrete with lathe waste as fiber reinforcement. A commercial computational analysis software, ANSYS 15, was used to create the Finite Element Analysis model. FEA results are numerically and graphically presented after testing specimens at various loads until failure.

2. Materials and Methods

For the compression and flexure test, concrete samples were casted for destructive testing and drawn in ANSYS design modular [29], both the test was carried out on cylindrical and beam specimen samples as per ASTM C39/C39M-21 and ASTM C293/C293M-16 standard sizes of concrete cylinder and beam [30], [31], [32]. Each mixture of Fiber-reinforced concrete specimens was designated as the FRC1, FRC2, FRC3, FRC4, FRC5, and FRC6, and was compared to the control specimen having no fibers [33]. The addition of lathe waste steel fibers at 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% [34] was incorporated into concrete [35]. There were total of six different percentages of lathe waste steel added to the concrete mixture [36]-[37]. These specific percentages were chosen based on preliminary studies from different literature review onto strength enhancement balance, and observe the effect of incremental fiber addition on the mechanical properties.

Furthermore for computational analysis the type of analysis known as explicit dynamics was chosen to be utilized in this Finite Element Analysis [38, 39]. Control and fiber-reinforced concrete cylindrical and beam specimens were subjected to a range of load increments in order to conduct experiments on them until they reached the point where they eventually failed in ANYS work bench. The same sizes, boundaries, and loading conditions are applied as on the Universal Testing Machine. As a means to overcome practical limitations, FEA was selected to perform a detailed simulation of the load effects on the specimens, allowing insights much faster and at a lower cost than physical testing.

2.1. Computational Analysis

On the ANSYS workbench, the first step was to create the geometry for the concrete beam and cylindrical specimens [39]. The dimensions of the concrete cylinder were 152 millimeters in diameter and 304 millimeters in height [40]. For the purpose of applying load, two discs were fastened to the ends of the cylindrical specimen. The lower disc has been fixed, while the upper disc was made free for application of loads until failure of specimen [30]. On the other hand, the beam had dimensions of 152 millimeters in diameter, 152 millimeters in height, and 609 millimeters in length [41]-[42]. The beam consisted of a simple supported beam with both ends roller supported and an impactor placed on top to apply center point load. Loads were applied at the longitudinal center of the beam to determine its flexural strength [42]. This loading condition methodology was developed for the same purpose as the universal testing machine [UTM], which is to achieve the same function [30]-[42]. This setup replicates UTM loading conditions, as well as guaranteeing the consistency and reliability of testing before a comparison of the experimental and computational results can be made.

A significant amount of importance is placed on the process of defining the appropriate boundary conditions for the structural analysis [43]. We consider two types of boundary conditions: supports and loads [44]. Supports are used to constrain the structure while loads are used to deform the structure. The outcomes may differ if the local constraints on the supports or loads are not defined correctly. In light of this, it is essential to explicitly define the boundary conditions that are responsible for supporting the loads that are applied to the cylinder and beam in this finite element model respectively [45]. The surface of the impactor and the disc have been calibrated to correspond with the pressure that is being applied to the fiber-reinforced concrete cylinder and beam. In the case compressive strength the steel plate is free, the pressure [P] that is applied is distributed evenly across the surface of the entire plate as done in Universal Testing machine [UTM] [30],[42]. When pressure is applied to the surface of impactors, the red area displays the surface, and the blue area displays the surface of fixed supports. An illustration of the boundary conditions of the concrete specimen during the preprocessor stage was defined. For application of load, load propeller was created for application of load until beam model fractures. These configurations result in the computational model having an accurate representation of load applications as in Universal testing machine, and thereby a reliable basis for determining structural responses of fiber reinforced concrete under load.

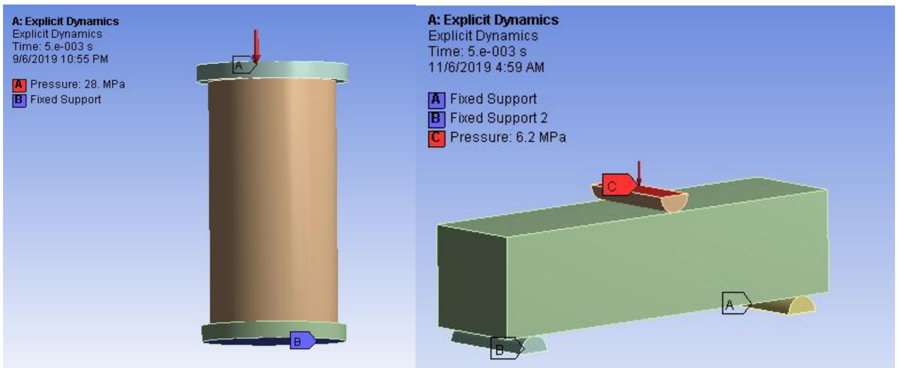


Figure 1. Boundary condition for compressive and flexural strength evaluation

Computational time and accuracy are both impacted by the size of the element [46]. The average mesh size for the control specimen was 3 millimeters, while the mesh size for the fiber-reinforced concrete specimens was 6 millimeters. This was determined based on some attempts to estimate an optimal element size [47]. The use of this distinction in mesh sizing enabled a balance between computational efficiency and result accuracy, thereby making the simulation as efficient as possible without forgoing model reliability.

For the purpose of incorporating fibers into concrete specimens, it is necessary to create three-dimensional lines in a spreadsheet created in Excel [48]. The length of each straight fiber that is generated by the spreadsheet. The spreadsheet generates straight fibers that are randomly oriented and dispersed evenly in concrete cylindrical and beam specimen. Following that, these fibers were dispersed in a manner that was completely random throughout a volume of concrete cylinder and beam [49], respectively. It is also possible to modify the spreadsheet in order to generate fibers of a predetermined length [50], [51]. The columns of the spreadsheet are transferred into text file, which is then read into the design modeler when it is opened. The use of this approach improved the distribution of fibers in the concrete matrix, which led to more accurate simulation of the influence of fiber reinforcement on mechanical properties.

Detailed calculation for cylindrical and beam specimen of lathe waste to be incorporated in cylinder and beam specimen for compressive and flexure strength in ANSYS workbench. Number of lathe waste incorporated in concrete is shown in Table 1.

Table 1. Volumetric for cylindrical and beam specimen of lathe waste.

Lathe waste steel Fiber volume	L×B×t = 1.5 ×0.2×0.1= 0.03 inch3 [L = 1.5 ich, B = 0.2-inch, t = 0.1 inch]	
Cylinder volume	$\frac{\pi}{4}$ d2×h=$\frac{\pi}{4}$ 62×12 =339.12 inch3 [h = 12-inch, d= 6 inch]	
Beam volume	L×B×H= 6×6×24 = 864 inch3 [L = 6-inch, B = 6-inch H = 24 inch]	
Number Lathe waste steel Fibers	0.5% by cylinder volume	0.5% beam volume
	V0.5 = 0.5/100 × 339.12 = 1.695 inch3 Numbers of fibers = NF = V0.5/VF = 1.695/0.03 = 56.52 fibers	V0.5 = 0.5/100 × 864 = 4.32 inch3 Numbers of fibers = NF = V0.5/VF = 4.32/0.03 = 144 fibers

After calculation of number of fibers for remaining incorporation of percentage of fibers the following table is drawn. Table shows the detail of number of fibers for each percentage of fiber addition in concrete specimen by volume.

Table 1. Composition of concrete and beam specimen incorporation for compressive and flexure strength in ANSYS workbench

Concrete Cylindrical Specimen		
Designation of fiber reinforced concrete	**Percentage of steel fibers [Lathe waste]**	**Steel fibers [Lathe waste] No's**
Control Mix M_0	0	0
FRC1	0.5	56
FRC2	1	112
FRC3	1.5	168
FRC4	2	224
FRC5	2.5	280
FRC6	3	336
Concrete Beam Specimen		
Control Mix	0	0
FRC1	0.5	144
FRC2	1	288
FRC3	1.5	432
FRC4	2	576
FRC5	2.5	720
FRC6	3	864

The solution phase is distinguished by the fact that all processes take place automatically. The generation of element matrices is the responsibility of the software, which is a component of the process of finite element analysis [FEA] [39]. In addition to this, the software is capable of computing nodal values and derivatives, and it stores the data that is generated in files. Following the phase known as "post processing," which makes review and analyses the results through the representation of the graphic display, while the post processing phase is the subsequent phase. There is a numerical output that is produced during the solution phase. The solution phase is responsible for producing output [52]. For each matrix load was predefine, the intensity of load was increased or decreased to find actual failure load for each cylindrical and beam specimen under testing [53]. An illustration of failure of specimen is presented in results section which would be the fact that the output of structural analysis and deformation. A variety of load increments were applied to the specimens of the cylinder and beam to ascertain the point at which they failed [54]. This was done to determine the ultimate load at which the cylinder and beam failed. By using these procedures it was possible to examine exactly how fiber reinforced concrete specimens behave to different loads and to verify the enhanced structural performance of the fiber inclusion.

2.2. Experimental Analysis

2.2.1 Compressive strength

Subsequently after respective curing age concrete specimen were tested for compressive strength. The compression test could be performed after getting out the samples from water as soon as possible. With the help of cloth cleaned the upper and lower plates of the universal testing machine. The cylindrical samples were placed in the universal testing machine. The universal testing machine was switch on and load was applied at constant loading rate. After failure of the concrete cylindrical sample measure the value of load.

$$f_c' = \frac{P}{A} \tag{1}$$

Where f'_c is compressive strength, MPa, P = maximum applied load indicated by the testing machine, N (lbf), A is cross sectional area of concrete cylinder (mm^2)

2.3. 2.2.2 Flexure strength

To elaborate the dimensions of specified section of specimen for use in calculating modulus of rupture, measurements across one of the fractured faces were taken after testing.

The modulus of rupture of control and fiber reinforced specimen were calculated as follows:

$$R = \frac{3PL}{2bd^2}\left(ASTM\ C-293/C293M-10\right) \tag{2}$$

Where R = modulus of rupture, MPa (psi), P = maximum applied load indicated by the testing machine, N (lbf), L = span length, mm (in), b = average width of specimen, at the fracture, mm (in), d = average depth of specimen, at the fracture, mm (in)

3. Results

Compression was carried out on cylindrical concrete model drawn in ANSYS design modular and on Universal Testing Machine. The addition was done on 0.5% raise and was added up to 3% i-e 0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3%. The concrete cylindrical specimens were analyzed at various load increments until failure load. The experimental results obtained from the specimens tested on universal testing machine were compared with the results obtained from computational analysis (ANSYS).

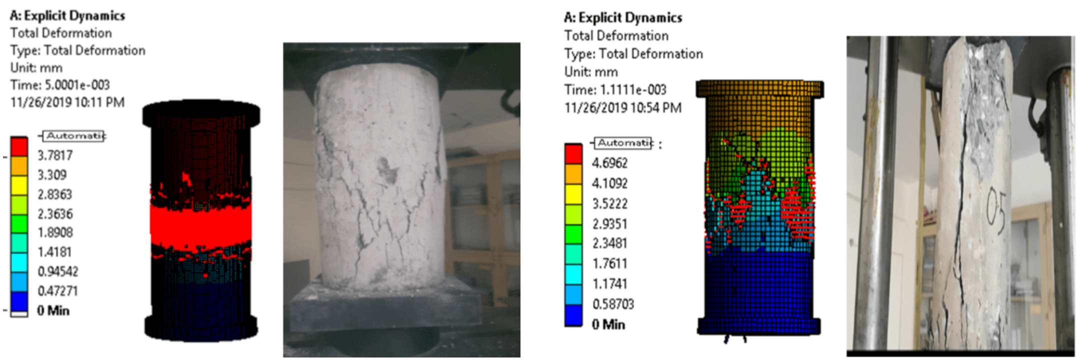


Figure 2. Comparative analysis of concrete cylinder (M_0 & FRC1)

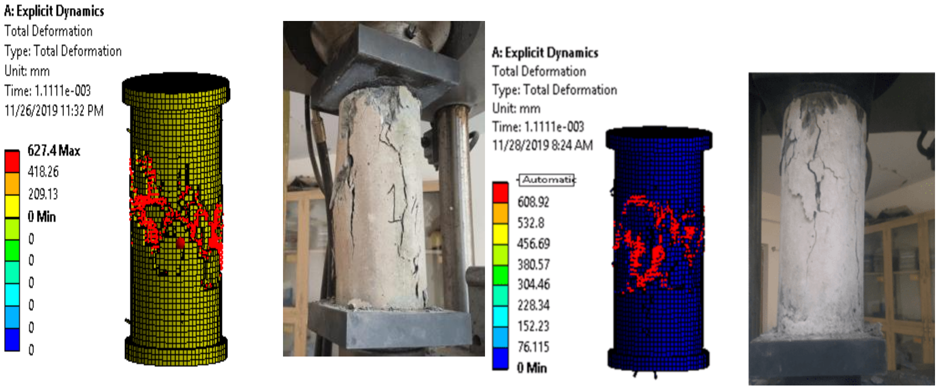


Figure 3. Comparative analysis of concrete cylinder (FRC 2 & FRC 3)

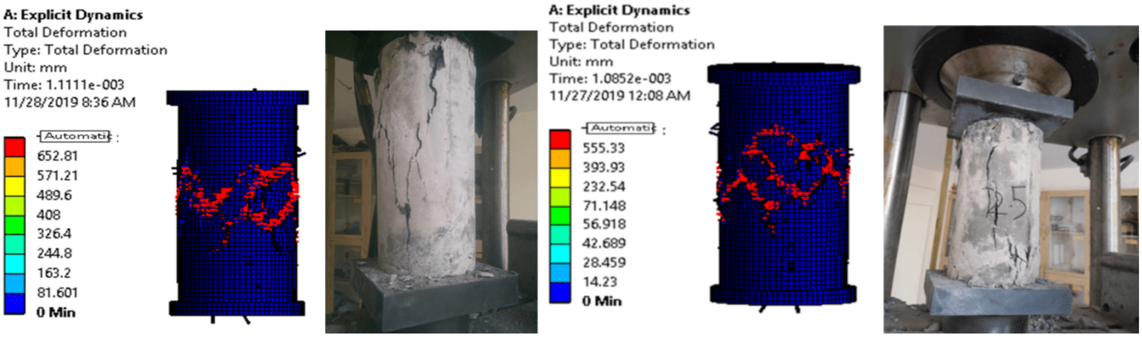


Figure 4. Comparative analysis of concrete cylinder (FRC 4 & FRC 5)

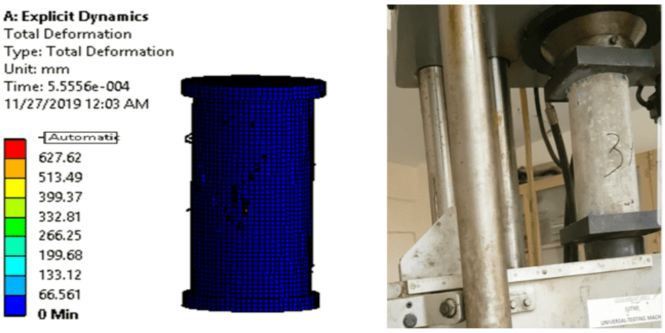
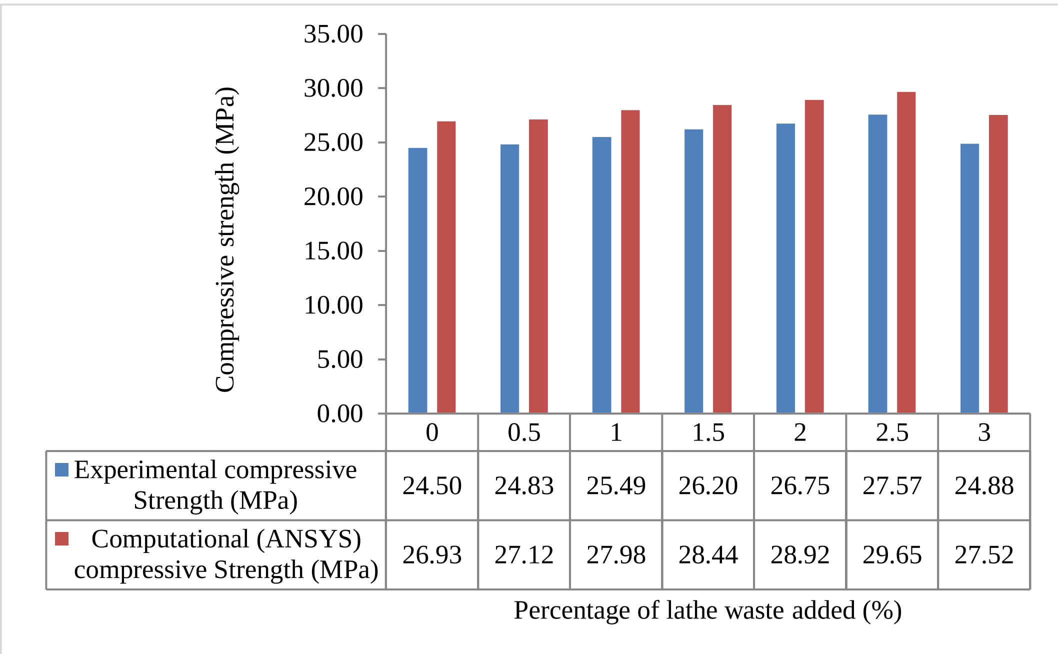
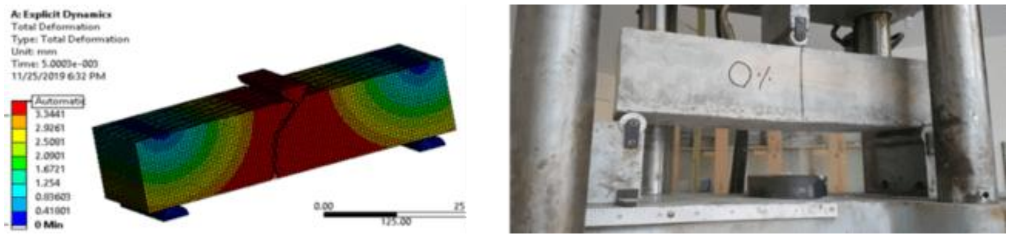


Figure 5. Comparative analysis of concrete cylinder (FRC 6)



	0	0.5	1	1.5	2	2.5	3
Experimental compressive Strength (MPa)	24.50	24.83	25.49	26.20	26.75	27.57	24.88
Computational (ANSYS) compressive Strength (MPa)	26.93	27.12	27.98	28.44	28.92	29.65	27.52

Figure 6. Destructive compressive strength vs Computation Analysis



Figuren7. Comparative analysis of concrete beam (M_0)

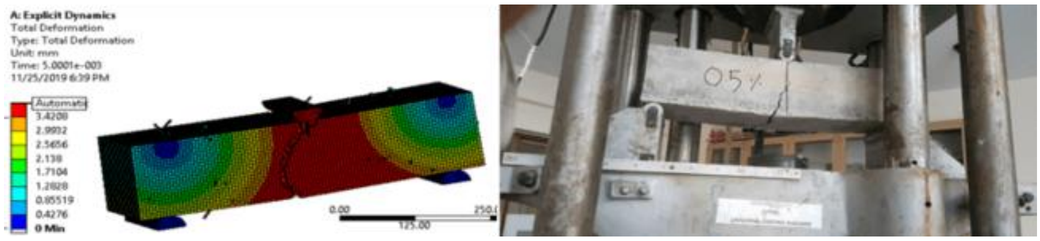


Figure 8. Comparative analysis of concrete beam (FRC 1)

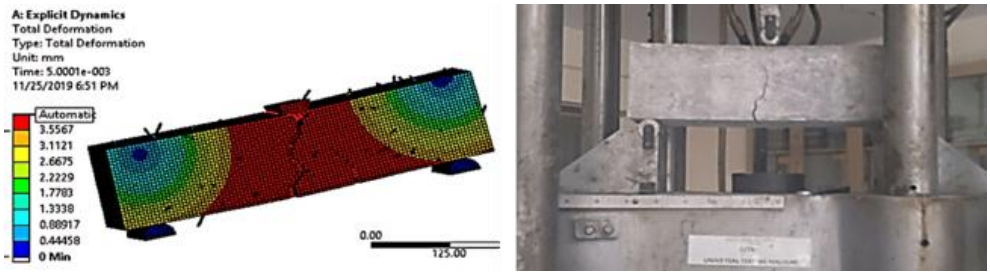


Figure 9. Comparative analysis of concrete beam (FRC 2)

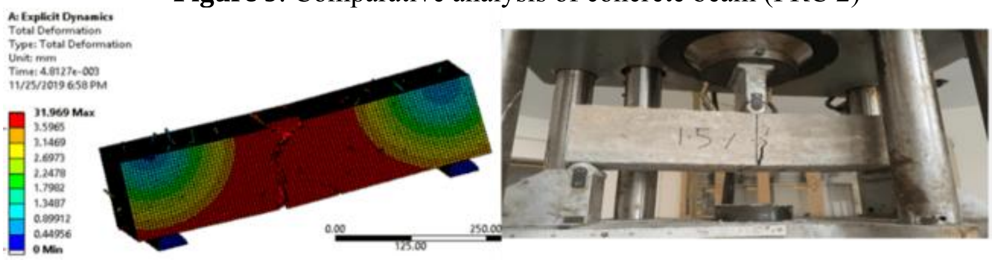


Figure 10. Comparative analysis of concrete beam (FRC 3)

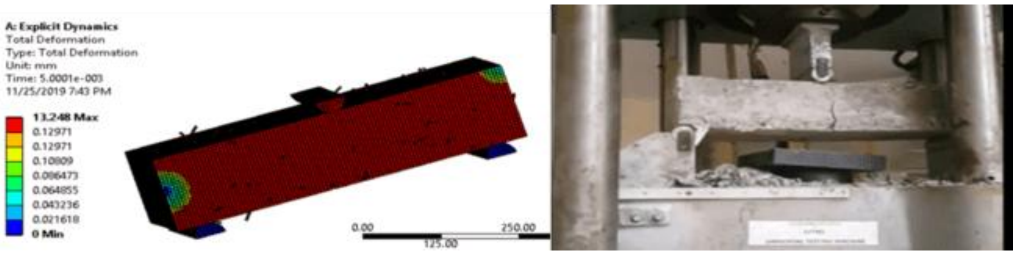


Figure 11. Comparative analysis of concrete beam (FRC 4)

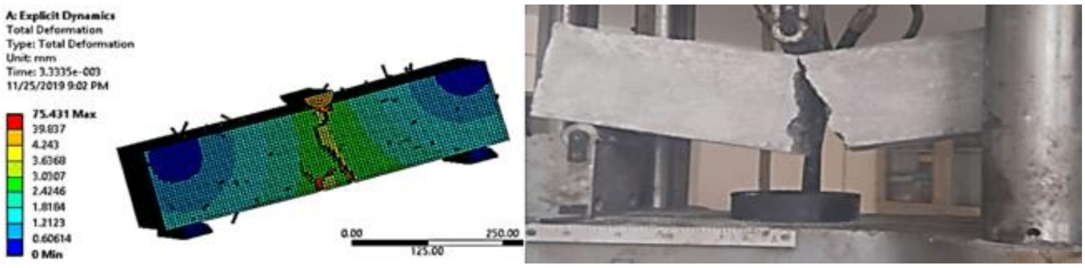


Figure 12. Comparative analysis of concrete beam (FRC 5)

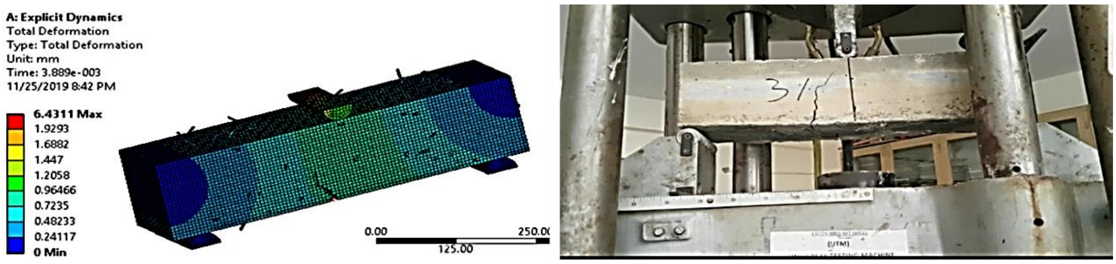
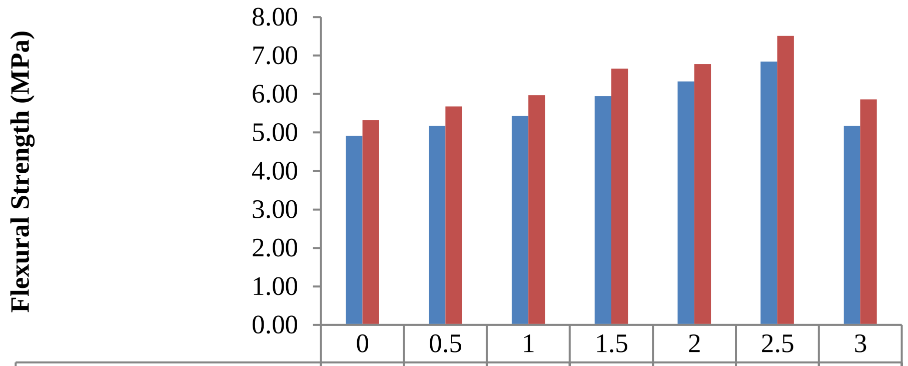


Figure 13. Comparative analysis of concrete beam (FRC 6)



	0	0.5	1	1.5	2	2.5	3
Experimental Flexural Strength (MPa)	4.91	5.17	5.43	5.94	6.33	6.85	5.17
Computational (ANSYS) Flexural Strength (MPa)	5.32	5.68	5.97	6.66	6.78	7.51	5.86

Figure 14. Destructive Flexure strength vs Computation Analysis

4. Discussion

The experimental results when compared to FEA analysis (ANSYS) are found to be varied. This difference in results might be due to accuracy of the ANSYS software. Also it was found that the analytical results were in good agreement with the experimental values. The study contributes to the development of new eco-friendly binder in concrete. Use of industrial waste products saves the environment and conserves natural resources. It can be extracted that by increasing lathe waste fiber compressive strength of specimen got increased gradually. It was also observed that specimens with 2.5% addition of lathe waste fibers have maximum strength when compared with control specimens. The failure mechanism of reinforced concrete cylinders modeled in FEA shows very close resemblance to the failure of specimen measured during experimentation which validate the FEA model.

Specifically, it is demonstrated that a gradual increase in compressive strength of lathe waste fiber containing composites as a function of fiber content to a maximum at 2.5% fiber inclusion, where maximum strength was observed relative to control specimens. Results confirm the contribution of lathe waste fibers to both ecological and structural improvements of concrete and underline their importance in sustainable construction. The stress-strain relationships until failure were achieved from FEA and compared against the experimental/empirical results. The stress-strain plots achieved from FEA shows good agreement with the empirical/experimental plots because when fibers are added the strain increase which mean fibers improve the brittle nature of concrete. In terms of this, FEA results and experimental data are consistent with each other in showing that fibers increase the concrete ductility and overall resilience.

It is possible to reduce the amount of deformation in a concrete cylindrical specimen using the amount of lathe waste steel and glass fiber employed can be evident in past related researches [55], [56], [35]. Concrete can be partially substituted with waste steel from lathes, and the shear strength of the material is enhanced. Compressive and flexure strength is increased as a result of the FRC cylinder and beam specimen gives superior performance in terms of its deformation characteristic in comparison to the control sample which is validated and consistent with recent works [36], [57]. For this reason, the addition of lathe waste steel results in an increase in the compressive and flexure strength of concrete, which is dependent on the properties of concrete. The same trend of strength was followed compressive and flexure strength. As a result of the compressive strength study, a similar pattern emerges in flexure strength. Increased incorporation of lathe waste steel to enhancement in bending strength. Compressive and flexural strength findings showed consistent improvement trend in mechanical properties, with addition of lathe waste steel fibers increasing the bending strength.

Non-destructive methodologies [NDM] have gained significant popularity in field testing due to its advantageous attributes such as high speed, cost-effectiveness, and ease of application. This trend has been observed in the past few decades. These methodologies possess the disadvantage of being indirect]. Numerous scholars have dedicated much time and effort over sever-al decades to the study of NDM. However, specialists in the field continue to strive towards the common objective of achieving accurate and reliable estimation of specific parameters in an efficient manner. The question of whether to integrate findings from destructive and non-destructive tests is a subject of ongoing [58]. In recent works findings from both destructive and non-destructive testing have been combined to furnish a more complete perspective of material performance. This approach emphasizes the opportunity of incorporating sustainable material testing in construction, yielding both environmental benefits and structural reliability.

5. Validation

To validate compressive and flexural strength, samples of ultimate proportion strengths were made and loaded until failure. SEM images below show micrographs obtained from scanning-electron microscopy of the fracture surfaces. The length of lathe waste steel fiber, combined with the applied force, causes the lathe waste broke rather than pulled out, resulting in a stronger bond in concrete. This increase in bond strength in the matrix resulted from more lathe waste steel fiber breaking in the concrete. Increases in bond strength at the lathe waste steel fiber -matrix interface have been linked to increased matrix strength. Fracture surface can also provide insight into the failure mechanism of the lathe waste steel in the concrete. It has also been observed that some of the lathe waste steel fiber is being extracted from the concrete. As a result, using lathe waste steel fibers can carry additional crack bridging loads without breaking. For example, increasing the diameter of lathe waste steel fibers can significantly improve the strength and toughness performance of concrete.

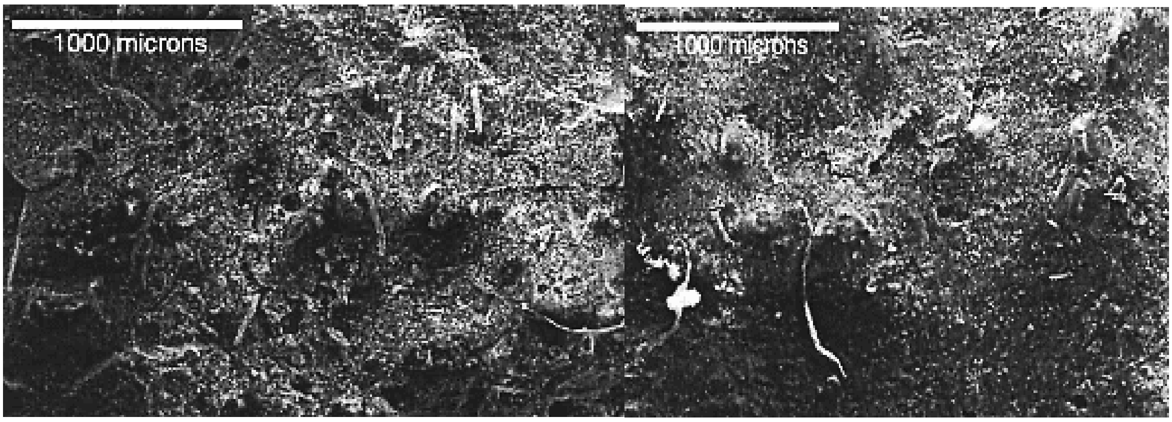


Figure 15. Scanning Electron Microscope Micrographs of fracture surface

6. Conclusion

The use of ANSYS to investigate the incorporation of lathe waste steel into concrete specimen results in reduced deformation means that the strength and performance of the material have considerably improved. This finding highlights the application of industrial waste materials as a means to improve the properties of concrete, a growing requirement in sustainable development. It can also be emphasized that the ultimate strength of the fiber reinforced concrete specimen was observed to increase when compared to conventional concrete. Enhanced ultimate strength of the investigated concrete can be attributed to the fiber reinforcement by flexible and ductile fibers, compared to brittle steel fibers only. Fiber reinforcement with lathe waste steel increases strength. Based on concrete volume, lathe waste steel fiber should be up to 2.5%.

The analysis also shows that finite element analysis is a non-destructive testing method. Finite element analysis, as an NDT method, is essential since it is cost-effective, saves time, and does not damage the concrete specimen, unlike the conventional UTM. The construction industry has been revolutionized by a novel finite element analysis of concrete matrix in which lathe waste steel fibers and glass fibers incorporation were used. The provided SEM images verified the strengths that the length of lathe waste steel fiber over the applied force act to cause the lathe waste to break in the concrete matrix. As result a greater bond in concrete because the lathe waste and glass fibers broke instead of pulling out. The demonstration of this bonding enhancement shows the practicality of fiber reinforced concrete as applied to real world projects where the enhanced strength and durability will prolong the life of infrastructure and maintain the lifecycles without frequent maintenance.

Beyond applicable to materials within the construction industry, this approach has broader implications for sustainable construction: it demonstrates the feasibility in commercial or infrastructural projects that not only reinforce materials, but also minimizing waste, support green building, and address environmental issues. Integrating such waste materials into concrete allows the construction industry to adopt eco-friendlier practices.

7. Data Availability Statement

All the data is provided in the article.

8. Acknowledgments

The authors would like to acknowledge the support of the Civil Engineering Department, Lincoln University College.

9. Conflicts Of Interest

The authors declare no conflicts of interest.

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