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Evaluation of the microstructural and mechanical properties of eco-friendly concrete reinforced with recycled wind turbine blades

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ABSTRACT

This paper presents the feasibility of utilizing Wind Turbine Blade (WTB) wastes as an alternative for the natural aggregate in cement concrete. Three types of experimental investigations were conducted to assess the potential of WTB combined with natural aggregate in concrete. As preliminary investigation, porosity property of the WTB aggregate is determined by water absorption test. Similarly, toughness and impact resistance properties are verified by aggregate impact and crushing tests respectively. An attempt has been made to study the influence of waste WTB as a substitute for natural aggregates in concrete for M25 grade at replacement percentage of 10, 20, 30, 40, and 50. Mechanical properties of developed concrete are evaluated by compressive strength, flexural strength and split tensile strength tests. Based on the results, 20% WTB waste substituted concrete had 8.5%, 14.7%, and 8.9% higher compressive strength, split tensile strength, and flexural strength than conventional concrete. The strength increment in the developed concrete is confirmed through microstructural evaluation using SEM micrographs, XRD and FTIR. Based on the investigation-conducted use of WTBs seems to have prospective applications in concrete with economic and environmental benefits preventing the accumulation of landfills of WTBs paving way for sustainability.

Keywords: Wind Turbine blades; EOL; Natural aggregates; Reuse; Sustainability.

1. INTRODUCTION

Concrete is one of the most consumed material next to water and it also causes 8% global CO_2 emissions [1]. In the global cement production landscape, India holds the position of the second-largest producer, contributing over 7% to the total installed capacity. For the financial year 2022, the country's domestic cement production reached 356 million tons, marking an increase from 296 million tons recorded in FY 2021 [2]. In concrete production, ten tonnes of aggregates required for one ton of cement [3]. Global Aggregate Information Network (GAIN) estimates the global aggregate demand will is likely increase to 60 billion tonnes per annum by 2030 [4]. The massive extraction of natural aggregates impacts the environment and consumes excessive energy. In past decades, many researchers have been using various waste materials, such as plastic waste, electronic waste, construction and demolition waste, agricultural waste, etc., as alternatives for aggregates in concrete to avoid the extraction of natural aggregates [5–9]. An alternate to natural aggregates is the need of the hour aiming sustainability.

India is extending its arms for adoption and development of innovative strategies in energy sector owing to the increasing demand. Look out for technology integration to serve as substitute for conventional resources is of foremost importance. This presents a variety of opportunity in power sector's value chain after addressing the challenges in terms of design, construction and installation of wind turbines and farms. Electricity power generation through Wind Energy (WE) is one of the best methods which is extensively used across the globe. Wind Turbine (WT) is a device which converts the WE into electrical energy. It is well known fact that WE is the clean and carbon-free renewable energy with lower environmental impact. According to Renewable Capacity Statistics 2023, China produced 365.93 GW WE in 2020. Similarly, USA and Germany produced 149.42 GW and 173.42 GW of WE in 0. India holds the 4th position in WE production. In 2022, India produced 41.93 GW of WE. India is highly reliable on conventional sources for energy production [10]. More than 60% of energy production in India is carried out with the help of thermal energy powered by fossil fuels [11–13].

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An average life of a WT is 25 years and 85% of the WT's components like gears, generator, foundations steel and copper wires are recycled/reused expect its blade. WTBs are made up of fibre composite materials like glass fibre reinforced epoxy, carbon fibre reinforced epoxy, glass fibre reinforced polyester. These fibre composite polymers are termed as Fibre Reinforced Polymers (FRP). Europe Wind Energy Association report stated that the 12 and 15 tonnes of composites materials used for generating 1 MW power generation. They also predicted the amount composite materials utilization in 2000-2030 as depicted in Figure 1 [14].

The Ministry of New and Renewable Energy (MNRE) report on December 2023, India installed Wind Energy (WE) capacity of 44.74 GW. The growth and number of turbines keep increasing every year (Figure 2), the older ones would reach End-of-life (EoL). The performance of the WT is reduced after it is reached its design life. These WTs are termed as inoperable WTs. ORTEGON *et al*. [15] listed (Figure 3) the various type of wastes available from the inoperable wind turbines and methods for recycling. Recycling of these blades has been a big challenge across the globe. Globally most of the developed countries are going to reduce the number of WTs because of the absence of proper recycling techniques. According to Bloomberg NEF, aging blades are becoming a waste around the world and most of these wastes may be disposed as landfills, of which the major contribution is from US and Europe [16]. If this is not properly handled, then it would have a major impact on environment. Most common method of disposal of WT blades earlier were land filling and incineration.

In India, installation of WT in drastically increased from 2005 onwards. Approximately, 4.68 million tonnes (from 2006 to 2021) of fibre composites materials have been used in the WTB manufacturing. In that most of the WTs (installed since 2006) going to reach their End-of-life (EoL). These wastes are going to increase from 2030. From Figure 2, it is evident that, generation of fibre composite wastes in India (MT) in 2030 is about 50000 MT and the projected fibre composite waste for 2045 is about 400000 MT which is 8 times higher. These quantities are calculated using European Wind Energy report are shown in Figure 4.

Most common method of disposal of WT blades earlier were land filling and incineration [17]. Reduction of waste dumped as landfill and landfilling ban of hazardous materials needs to be incorporated [18]. Use of materials recycled materials as substitute for natural materials reduces landfill [19]. WTBs are regarded as components of composite materials that cannot be recycled [20].

ALMEIDA *et al*. [21] investigated the use of ceramic scrap in varying amounts as a coarse aggregate in the concrete's composition. The average values reported for the compression strength, including the formulation using 100% ceramic scrap (fc = 47.78 MPa), were excellent. The little adhesion between the ceramic trash and the mortar as a result of the waste's glazing in its shape was another significant feature of the rupture modes that was noticed. Compressive strength and ductility behavior may be enhanced by the combination of oil Palm Shell (OPS) and Palm Oil Clinker (POC). The regular coarse aggregate in the lightweight concrete used in this experiment is swapped out for a combination of OPS and POC aggregates. There are differences between 40% and 70% in the percentage of POC and OPS in the concrete mix [22].

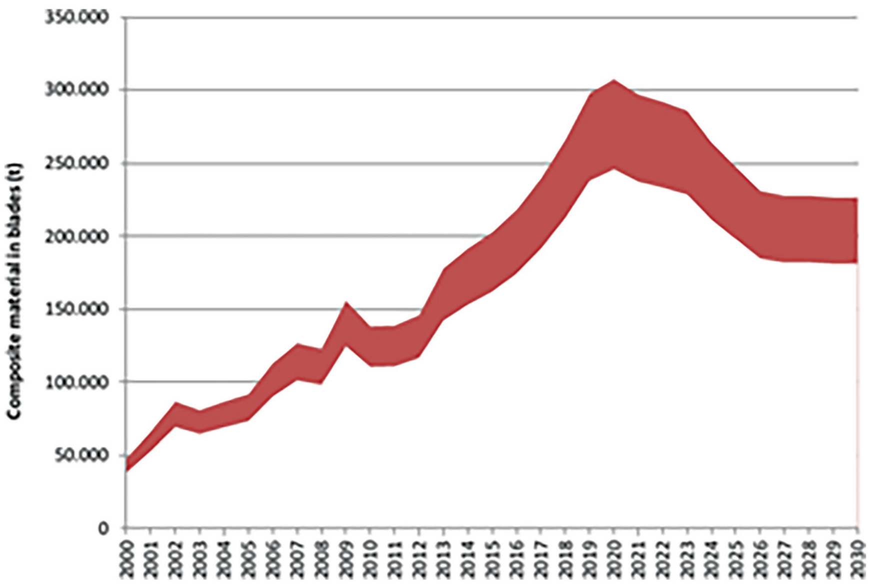

Figure 1: Annual use of FRP composites in WTBs [14].

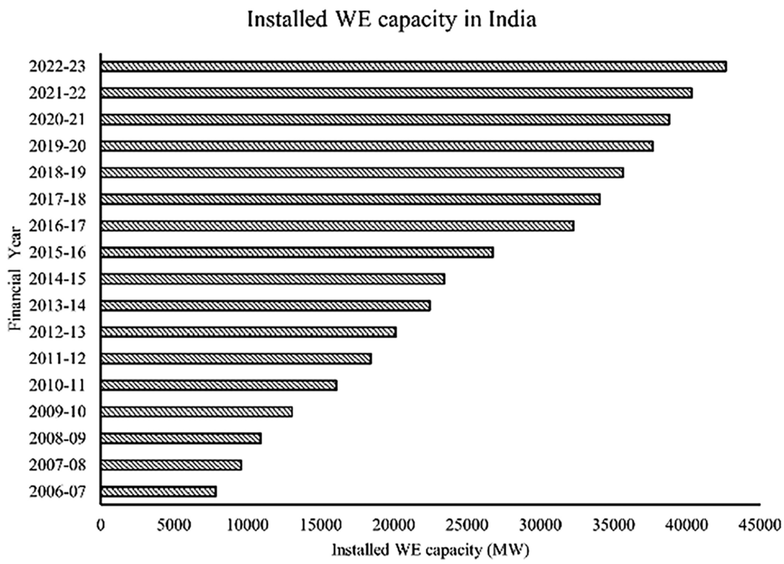

Figure 2: Installed WE capacities in India.

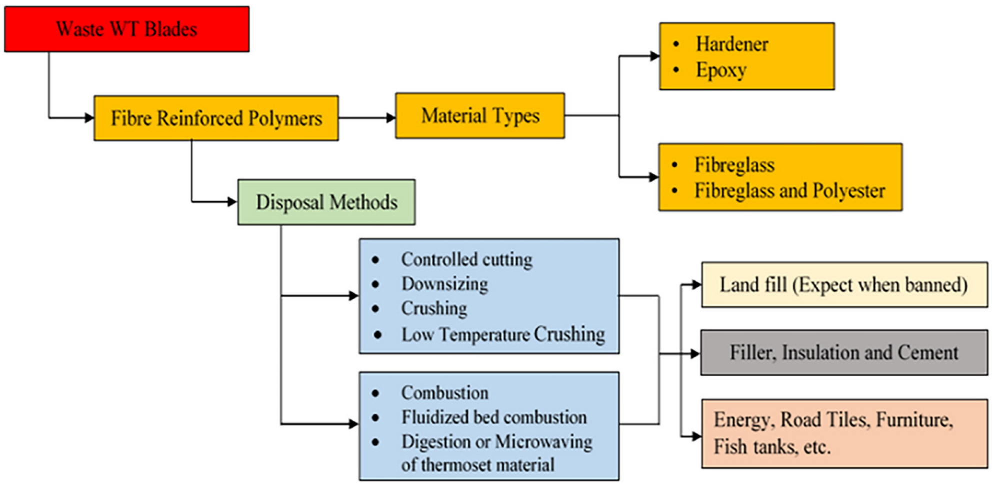

Figure 3: Typical disposal process of WT blades [15].

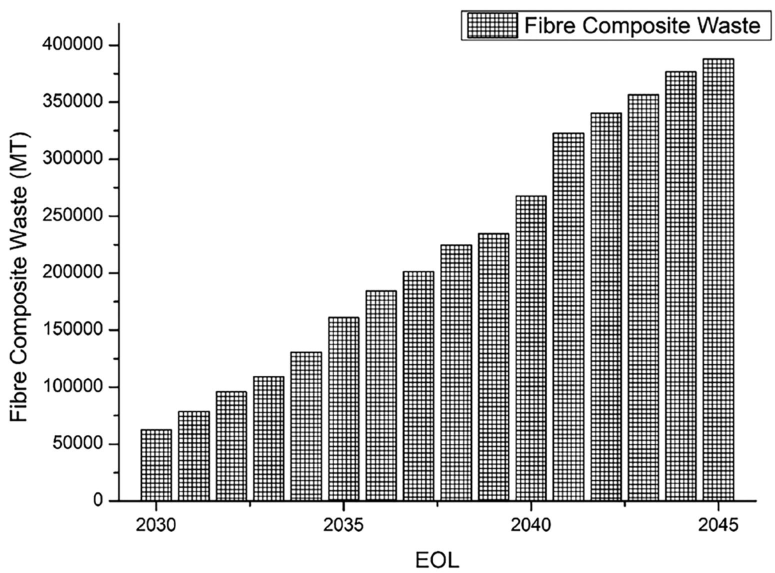

Figure 4: Projected fibre composite waste for 2045.

It is evident that the number of turbines reaching EOL in India will be more and estimation of waste generation from wind turbines reaching EOL are higher. If this is not properly handled then it would have a major impact on environment [23, 24]. Most common method of disposal of WT blades earlier were land filling and incineration [25, 26] utilized the shredded composite (SC) from WTBs in newly created thermoset composites and discovered that SC required chemical processing to increase its adherence to the resin matrix.

Prior research indicates that the rate of absorption for cut fibre reinforced polymer rebars is poor, and complete absorption necessitates a duration significantly greater than the concrete's curing time [27]. The shape, resource, and interfacial bond conditions of the FRP aggregates influence the mechanical properties of concrete when it is used with FRP needles [28]. JENSEN and SKELTON [29] stated that the handling of waste WTBs represent a challenge due to the type of materials used and their complex composition.

World wind turbine blade waste is expected to reach over 43 million tons by 2025, according to estimates made by BANK *et al*. [30]. LIU *et al*. [31] stated that, WTBs one of the most important components in the wind turbines, made with composite, are currently regarded as unrecyclable.

Hence an initial attempt is made to develop a sustainable construction material from this non-decomposable fibre composite waste.

2. EXPERIMENTAL WORK

2.1. Materials and methods

2.1.1. Wind turbine blade waste aggregate

WTBs were normally made by compressing the thin layer of fibre sheet with epoxy resin to making it compacted and it has high tensile strength. In recent times, damaged WTBs converted into fibre boats, black boards, park benches etc. In this study, the authors collected the waste WTB from a fibre boat production industry located at Nagercoil, Tamil Nadu, India. After completing the preliminary investigation on the WTB, the primary foam layer is completely removed from the surface of fibre composites layers. Using mechanical cutting tool (Figure 5a), long blades are converted into small pieces. Typical cutting process of the fibre composite wastes is shown in Figure 5. Approximately, the size of the fibre composite aggregates (WTB waste) varies from 10 mm to 12 mm size.

The main intention of this study is to utilize the fibre composite waste as an alternative for the natural aggregates. Preliminary tests namely aggregate impact value test and aggregate crushing strength test were conducted to identify the basic properties of fibre composite aggregates. The obtained results compared with the properties of the normal coarse aggregates. The impact value of normal coarse aggregates and WTB aggregates are 28.5% and 5% respectively. The results clearly shows that WTB aggregates fall under exceptionally strong category whereas natural aggregates fall under satisfactory category. The same behaviour was observed for aggregate crushing strength tests (29.56% and 4% respectively). Specific gravity and water absorption of the WTB aggregate noted as 2.76 and 0.9% respectively.

The mix design used for these investigation's is of M25 grade concrete as per IS10262-2009 [32]. Based on the property of the materials and the mix design, proposed concrete having mix proportions of 1:2.3:3.6 and water cement ratio of 0.45. In addition, 0.5% Super Plasticizer (SP). Six different types of specimens were considered for this experimental investigation. The nominal mix without FCW was the first type (M0), and then 10% (M1), 20% (M2), 30% (M3), 40% (M4) and 50% (M5) replacement of coarse aggregate with the WTB aggregate was the remaining five types. Table 1 explains the proportions of the FCW incorporated concrete.

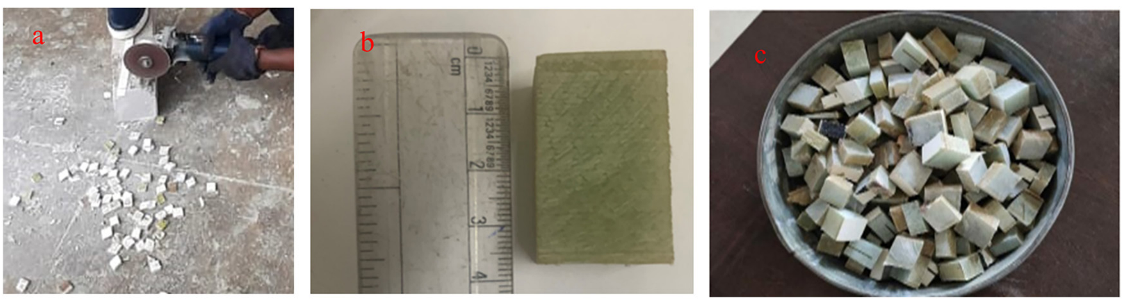

Figure 5: (A) Cutting machine, (B) Powdered form of WTB, (C) and (D) Resized FCW.

Table 1: Mix combinations for the development of FCW incorporate concrete.

SPECIMEN CODE	DESCRIPTION	CEMENT (kg/m³)	FCW (kg/m³)	COARSE AGGREGATE (kg/m³)	FINE AGGREGATE (kg/m³)	SP %
M0	Conventional	340	0	1215.64	778.36	0.5
M1	10% FCW incorporated	340	121.56	1094.08	778.36	0.5
M2	20% FCW incorporated	340	243.13	972.51	778.36	0.5
M3	30% FCW incorporated	340	364.69	849.95	778.36	0.5
M4	40% FCW incorporated	340	486.26	729.38	778.36	0.5
M5	50% FCW incorporated	340	607.82	607.82	778.36	0.5

Figure 6: FCW specimens after aggregate impact test.

2.2. Mixing and casting of specimens

The concrete composition is designed by the volume or weight of material in 1 m^3 of concrete or by the relative number of materials with the amount of binding material taken as unity. The specimen was casted with the coarse aggregate with the size 20 mm. The concrete was prepared from Ordinary Portland cement of 53 grade, coarse aggregate, fibre composite waste and water. Totally, 36 numbers of 150 mm cube specimens, 36 numbers of 150 mm × 300 mm cylindrical specimens and 36 numbers of 100 mm × 110 mm × 500 mm prism specimens were casted.

2.2.1. Preliminary tests conducted

The impact value of normal coarse aggregates and WTB aggregates are 28.5% and 5% respectively. The results clearly shows that WTB aggregates fall under exceptionally strong category whereas natural aggregates falls under satisfactory category. The same behaviour was observed for aggregate crushing strength tests 29.56% and 4% respectively. From the Figure 6 it is evident that the FCW aggregates exhibit combination of multiple composite fibre matrix. The specimens are not crushed under impact loading unlike natural aggregates. This is attributed to the epoxy layers between fibres.

3. MATERIAL CHARACTERIZATION

3.1. X-ray diffraction (XRD)

Figure 7 depicts the X-ray diffraction (XRD) spectrum of wind turbine blades replaced concrete. The spectrum reveals the existence of a feature of glassy phase exhibited by amorphous hump approximately between 20 and 35^o 2θ, which clearly shows the presence of amorphous materials, which increases the probability of pozzolanic reaction that contribute to durability and mechanical strength development. The XRD analysis confirms the high content of SiO_2 along with CaO that contribute to pozzolanic reaction forming C-S-H-calcium silicate hydrate.

3.2. Scanning Electron Microscopic analysis

The characterization of the WTB waste is analyzed using SEM analysis in Figure 8a. SEM analysis shows the morphology of waste material, fibres between the lengths of 200 nm to 20 µm were observed. Fine particles visualised on fibers surface shows presence of aluminium silicon and sodium, which confirms it, belongs to type R fibers that will be strong and corrosion resistant.

The SEM morphology of the developed concrete using WTB wastes coarse aggregate is shown in Figure 8b SEM analysis indicated the matrix of different graded particles including the WTB. The matrix shows compacted and dense microstructure because of the thick layers of gel covering the unhydrated particles and voids that is hardly observed. The SEM image presents fewer dark spaces, which confirms a denser matrix. This shows that the hydration process was better that had a formation of formation of C–S–H gel and C-A-S-H. C–S–H product would have raised binding of WTB aggregate and the binder making concrete denser thereby increasing the strength of developed concrete. Further correlating with XRD analysis confirms the development of C-S-H gel for strength and binding improvement.

3.3. FTIR analysis

FTIR analysis gives information about the molecular chain's organization. The results show the presence of Methyl (-CH3), Methyne (>CH-), Alkenyl (C=C), Aromatic nitro compounds as main components in the waste WTB. Figure 7 illustrates the FTIR of wind blades. Broad bands around 3429 cm^{-1}, 2925 and 2514 cm^{-1}

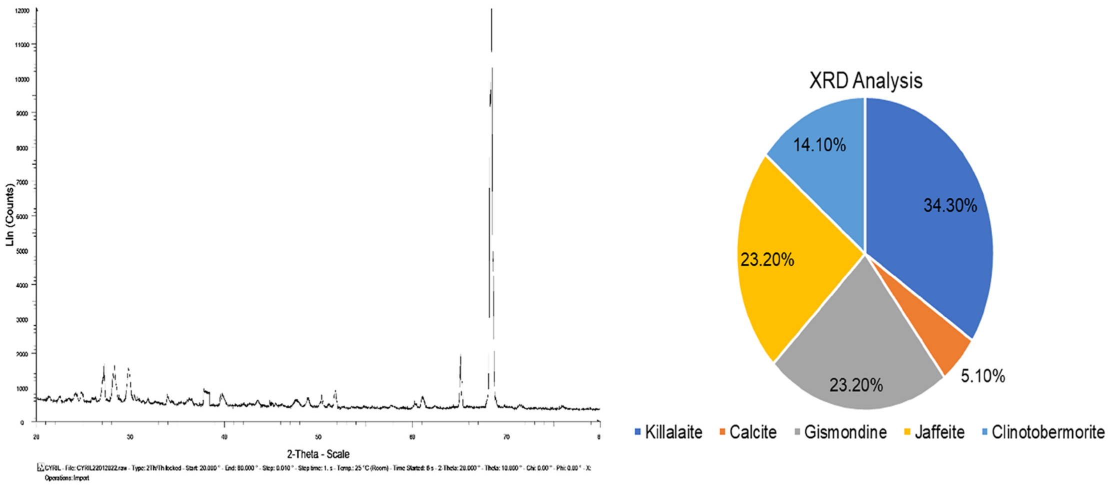

Figure 7: XRD of wind turbine blades.

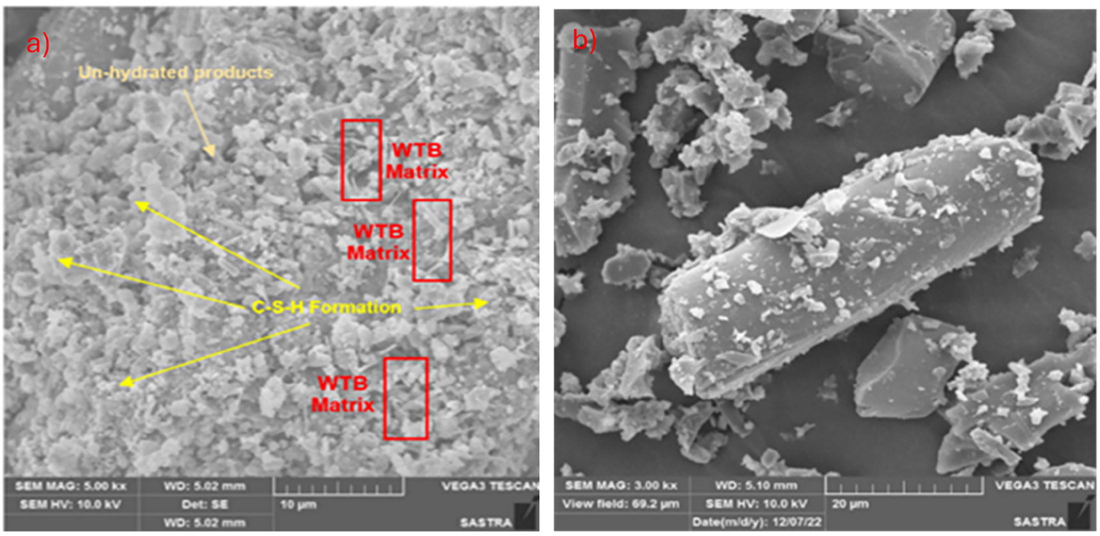

Figure 8: (A) Typical view of the WTB waste surface morphology. (B) SEM micrographs of developed concrete using wind turbine blades.

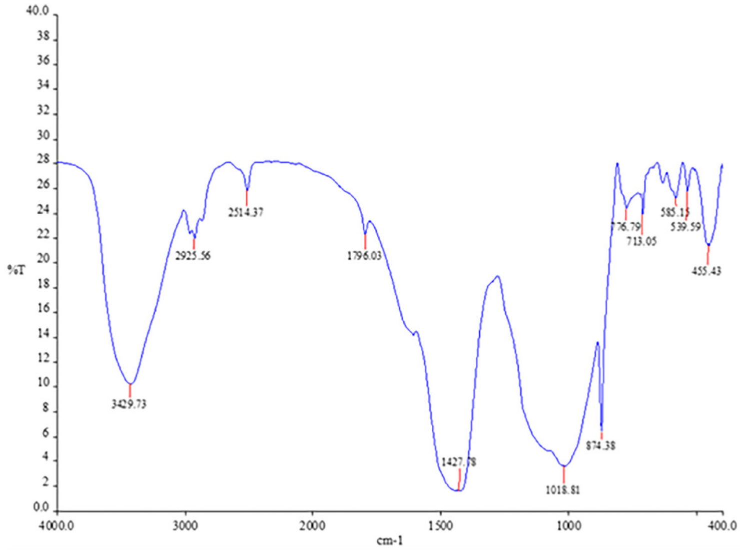

Figure 9: FTIR of wind turbine blades.

corresponds to the OAH stretching vibration under associated hydrogen-bonded inside molecules [33, 34]. Adsorption bands that are centered at 1796 cm^{-1} is owing to HOH bending. These absorption bands are signifying the crystalline hydrated products of water such as C–S–H and C–A–S–H gel. Stretching vibration of O-C-O bonds of carbonate groups was detected in specimen at 1427 cm^{-1} can be due to the carbonation reaction [35]. The vibrations at about 1018 cm^{-1} are due to the stretching vibrations of T-O-Si (T = tetrahedral Si or Al) (asymmetric) [36]. Fe-O bonds (Stretching vibrations) are associated with 776–539 cm^{-1}, and Fe-O stretching vibrations and O-T-O bending corresponds to spectra 585 to 455 cm^{-1} [37] (Figure 9).

4. MECHANICAL PROPERTIES OF DEVELOPED CONCRETE

Three major tests were conducted namely compression test, flexural test and split tensile strengths for assessing the mechanical properties of the developed concrete.

4.1. Compressive strength

The concrete is prepared in the required proportions and specimens are cast by filling the concrete in the desired mould shape of 15 cm × 15 cm × 15 cm cube with proper compaction. The test procedure are as per IS 516 (Part-1 Sec-I)-2021 [38]. The compacted mould kept at a temperature of 27° ± 2°C and 90% relative humidity for 24 hours. After 24 hours the cubes were removed from the mould, Curing is done with by immersed in clean fresh water until taken out for testing. A total of 18 cubes of size 150 × 150 × 150 mm were casted, after 24 hours the specimens were demoulded and are subjected to curing for 28 days. The cube Specimen was tested in a CTM (Figure 10a).

$$\text{COMPRESSIVE STRENGTH} = \text{LOAD} / \text{AREA } (N/mm^2)$$

The results shows that there is gradual increase in percentage of strength of concrete up to 20% replacement of WTB waste and then the strength of the developed concrete trends to decrease. The compressive strength of the 20% WTB waste replaced concrete is 8.5% higher than the conventional concrete (Figure 10b). An improvement in the ITZ's (interfacial transition zone) microstructure between coarse WTB and cement paste, strengthened their binding, and believed to have contributed to the higher performance.

The concrete's strength is largely dependent on the microstructural uniqueness of the ITZ between the recycled material and the binder [39]. The multiple layers of the fibre composites are bonded with epoxy resins offers the maximum resistance against the crushing. This results clearly shows that WTB aggregates fall under exceptionally strong category whereas natural aggregates fall under satisfactory category and hence WTB aggregates could have enhanced the strength aspects.

4.2. Split tensile strength

The concrete is prepared in the required proportions and specimens are cast by filling the concrete in the desired mould shape of 15 cm diameter 30 cm high cylinder with proper compaction. The test procedure follows to Is

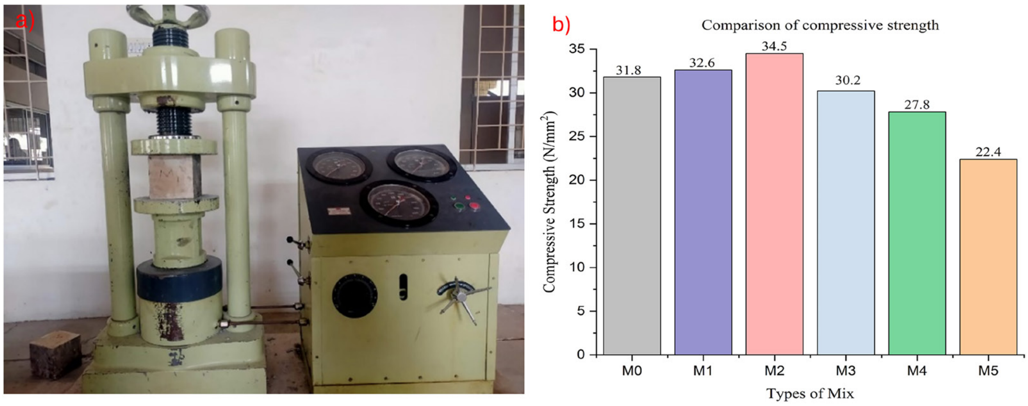

Figure 10: (A) Typical view of compression specimen. (B) Comparison of compressive strength of developed concrete.

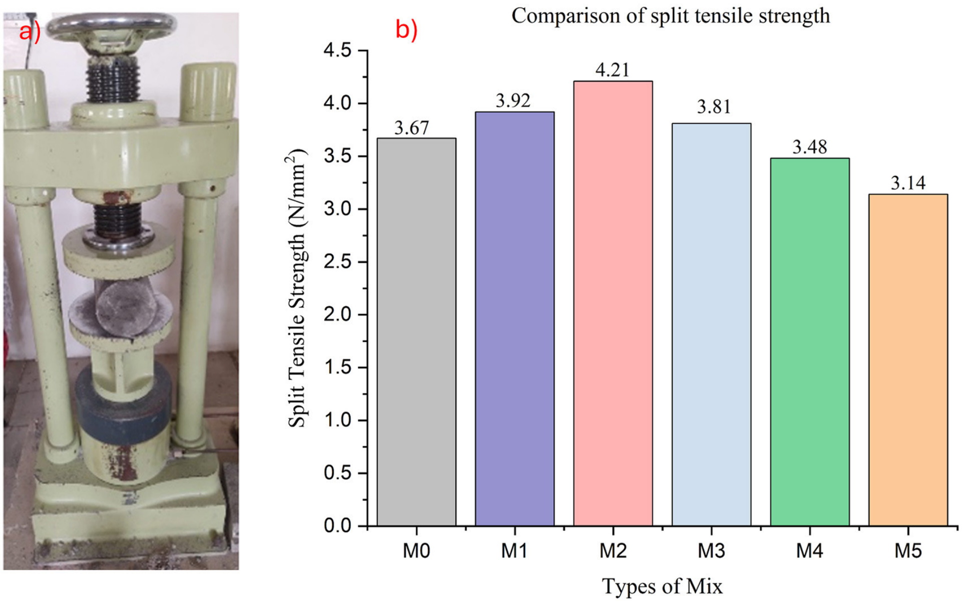

Figure 11: (A) Typical view of split tensile specimen. (B) Comparison of split tensile strength of developed concrete.

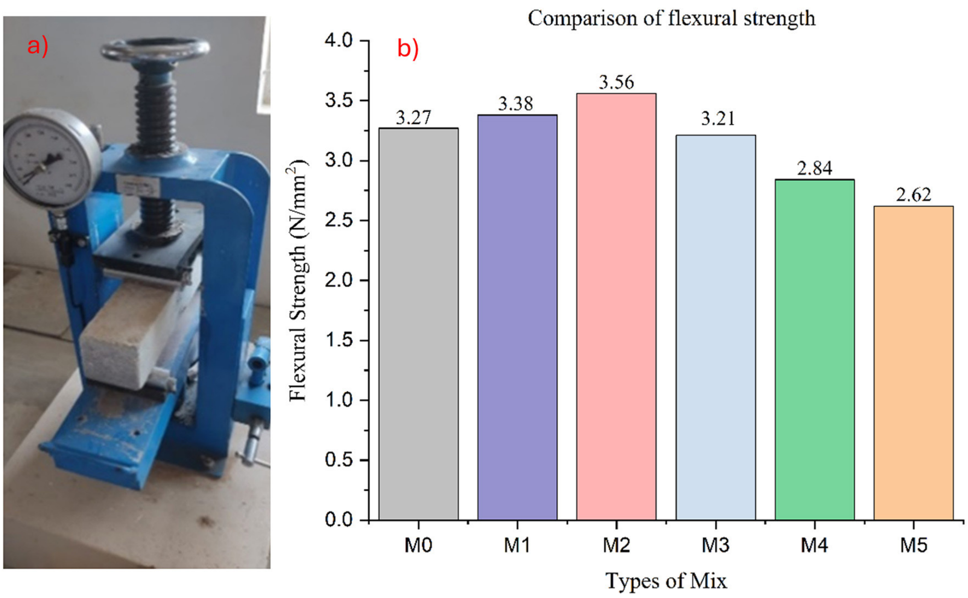

Figure 12: (A) Typical view of flexural specimen. (B) Comparison of flexural strength of developed concrete.

516 (Part-1 Sec-I)-2021 [38]. The compacted mould kept at a temperature of 27° ± 2°C and 90% relative humidity for 24 hours. After 24 hours the cylinder was removed from the mould, Curing is done with wet gunny bags for 28 days and immersed in clean fresh water until taken out for testing. The cylinder specimen was tested in a CTM after a curing period of 28 days and an average of the values gives split tensile strength test of the given pervious concrete sample.

SPLIT TENSILE STRENGTH TEST= (2P /πLd) in N/sq.mm

The split tensile strength of the concrete specimens for varying proportions of partial replacement was given below in Figure 11a and b. The split tensile strength of the lightweight concrete was tested by using Compression Testing Machine (CTM) of 2000 KN capacity (Figure 11a).

A total of 18 cylinder of size 150 × 300 mm were casted and tested for 28 days strength, each of 18 specimens after 24 hours in mould subjected to curing for 28 days.

The results shows that there is 14.7%, strength increment is observed in split tensile strength up to 20% replacement of WTB waste and then the strength trends to decrease (Figure 11b).

4.3. Flexural strength

The concrete is prepared in the required proportions and specimens are cast by filling the concrete in of size 100 mm × 110 mm × 500 mm prism specimens were casted. procedure follows to IS 516 (Part-1 Sec-I)-2021 [38] (Figure 12a).

From the results it is evident that there is 8,87%, strength increment is observed in flexural up to 20% replacement of WTB waste and then the strength trends to decrease (Figure 12b).

This favourable performance of the 20% replacement of WTB waste is attributed to enhanced aggregate sand filling impact particle packing. Larger surface area and consequent creation of superior extra C-S-H by WTB, leads to a denser microstructure and increased strength [40]. The thick layers of gel covering the hardly noticeable spaces and unhydrated particles give the matrix a compressed and dense microstructure. There are fewer black areas in the SEM image (Figure 8).

It was observed that the test specimens containing more than 20% WTB waste failed at lower loads as compared with those made of control concrete. Ideal failure patterns were observed in all test specimens. Due to the lack of bonding between the WTB waste aggregate and cement paste, strength reduction may occur in 30% to 50% replacements. The same behaviour was noticed in all the tests.

5. PRACTICAL APPLICATIONS

Based on the investigation, WTB waste gives a good result in aggregate impact test and aggregate crushing strength tests. The developed concrete can be effectively utilised in sustainable construction applications like base courses for pavement, structural and non-structural concrete elements. The CO_2 equivalents is expressed as

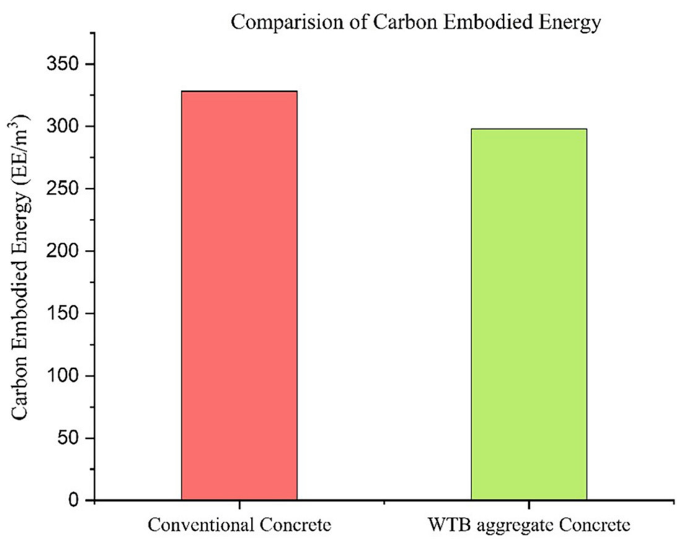

Figure 13: Comparison of embodied energy of developed concrete with conventional concrete.

$$E = \Sigma\,(w_e \times m)\ [\text{kg } CO_2 \text{ emission/m}^3] \quad (1)$$

w_e represent the activity emission factor, m represents substance unit of material used such as cement, fine and coarse aggregate & Chemical admixture), per 1 m^3 of concrete. The consideration of definition taken as per International Organization for Standardization (ISO). ISO 14067:2013. According to Inventory of Carbon and Energy (ICE) the percentage reduction of embodied energy for fibre composite developed concrete with 20% replacement of WTB as aggregates is reduced considerably in comparison to conventional concrete of same M25 grade without replacement (Figure 13).

6. CONCLUSIONS

The aggregate impact and aggregate crushing strength results reveals that WTB aggregates exhibit significantly higher values in comparison to the natural aggregates.

- The replacement of WTB aggregate, 10% and 20%, in concrete enhanced the compressive strength, split tensile strength and flexural strength, whilst 30% decreased them. The 20% replacement of WTB aggregate shows the maximum strength in all tests. The enhancement in compressive strength is noted as 8.5%. Similarly, 14.7%, 8.87% increment was noted in the split tensile strength and flexural strength respectively.
- The microstructure analysis reveals a good interfacial transition zone, suggesting a complete reaction. SEM investigation revealed the matrix of different graded particles, including the WTB aggregate. The matrix has compacted and dense microstructure because of the thick gel layers covering the hardly perceptible gaps and unhydrated particles. The XRD study verifies the high concentration of SiO_2 and CaO, which support the pozzolanic process that forms the calcium silicate hydrate C-S-H. The inclusion of WTB aggregate in concrete reasonably reduces the carbon embodied energy.
- In this study, 20% replacement of the WTB aggregate minimizes the carbon embodied energy by 10%. These findings suggest that WTB aggregates not only possess excellent mechanical properties but also exhibit low water absorption, making them a feasible and good alternative to natural aggregates in concrete applications.
- Further there is a necessity that potential solutions to be equipped for aiding the proper disposal and reuse of wind turbine blades in future. Sustainability aspects of wind turbines reaching the end of life is required for protecting the planet earth. Recycling and reuse of wind turbine blades has great challenges and needs to be explored in terms of civil engineering applications.

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