Strength And Sustainability Assessment of Biochar-Steel Reinforced Concrete

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Abstract - There is a pressing need for sustainable alternatives in the manufacturing of concrete because the cement sector is one of the main sources of carbon dioxide emissions worldwide. Through the partial substitution of biochar for cement at weight percentages of 0%, 2%, 4%, and 6%, as well as the addition of 1% crimped steel fibres to improve mechanical properties, this study examines the strength and sustainability performance of biochar steel fibre reinforced concrete (BSFRC).In order to identify the ideal replacement level, the experimental program assesses compressive strength, split tensile strength, and flexural strength at various curing times. A cradle-to-gate Life Cycle Assessment (LCA) approach is used to evaluate environmental performance. Embodied carbon and global warming potential (GWP) are quantified using an emission factor-based method. Each mix's carbon footprint is determined by taking into account the steps of raw material extraction, processing, and transportation. According to the results, adding crimped steel fibres enhances tensile and flexural performance and makes up for any potential strength losses, while adding biochar lowers cement usage and embodied carbon emissions. The 4% biochar replacement mix exhibits the best balance between mechanical strength and carbon reduction among the mixes examined. According to the study, biochar-based steel fibre reinforced concrete has the potential to be a sustainable building material that lowers carbon emissions and improves performance.

Key Words: Biochar; Steel Fibre Reinforced Concrete; Carbon Footprint; Cradle-to-Gate Life Cycle Assessment; Embodied Carbon; Sustainable Concrete; Compressive Strength; Global Warming Potential (GWP); Cement Replacement; Low-Carbon Construction Materials.

1. INTRODUCTION

The world's most used building material is concrete because of its tremendous compressive strength, resilience, and adaptability. In the construction of buildings, bridges, pavements, and hydraulic structures, it is essential. However, cement, the main binding ingredient in concrete, makes a substantial contribution to the world's emissions of carbon dioxide (CO_2). One of the main drivers of global greenhouse gas emissions is the energy-intensive processes and limestone calcination involved in cement production.

Facing these issues, A promising sustainable building material is biochar, a carbon-rich substance created by pyrolysing biomass in low-oxygen environments. When biochar is used in place of some of the cement, it can minimise embodied carbon and sequester carbon. Its porous structure may also improve its durability and internal curing properties. However, because biochar has a lesser binding capacity than cement, increasing percentages of biochar replacement may hurt mechanical strength. Crimped steel fibres are added to the concrete mixture to enhance tensile and flexural performance and make up for any potential strength loss. Steel fibres improve concrete's post-cracking behaviour, impact resistance, ductility, and crack resistance. To enhance the structural performance of concrete amended with biochar, 1% crimped steel fibres are added.

Sustainability is evaluated utilising a cradle-to-grave Life Cycle Assessment (LCA) method in addition to mechanical performance. The emission factor approach is used to calculate each mix's carbon footprint. The Global Warming Potential (GWP) is used to express the environmental impact. The main objective of this project is to develop a sustainable and high-performance concrete by partially replacing cement with biochar and enhancing strength characteristics using steel fibres.

Solutions are proposed to enhance both the mechanical performance and environmental sustainability of concrete. This study focuses on reducing the carbon footprint of conventional concrete by partially replacing cement with biochar derived from organic waste and improving structural performance through the incorporation of steel fibres. Additionally, mix proportions are optimised to achieve the best balance between strength and sustainability.

2. METHODOLOGY

2.1MATERIALS

- Cement

Cement is a binding material used for concrete. It binds the coarse and fine aggregates with water to form a monolithic mass and also fills the voids in the concrete. The cement used is PPC

- Fine & Coarse Aggregate

Fine aggregate consists of materials passing through a 4.75 mm sieve and is used to fill the voids between coarse aggregates, improving workability and strength. Clean and angular manufactured sand (M-sand) was used in this study. Coarse aggregate, retained on a 4.75 mm sieve, forms the main skeleton of concrete and provides strength and stability. Crushed granite of 20 mm size was used as the coarse aggregate to ensure durability and proper bonding in the mix.

- Steel Fibre

Crimped steel fibres were added to the concrete to improve its flexural strength, ductility, impact resistance, and crack control. The crimped shape provides better mechanical anchorage and bond with the concrete matrix, ensuring efficient stress transfer. The fibres were uniformly distributed throughout the mix to form fibre-reinforced concrete with improved toughness and post-cracking behaviour.

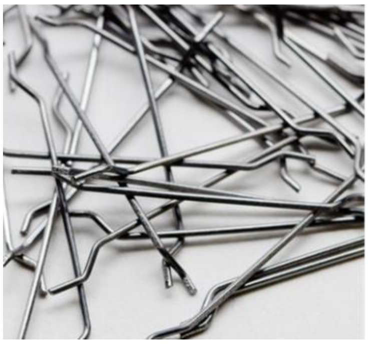

Fig. 1: Steel Fibre

- Biochar

Biochar, a fine carbon-rich material obtained from the pyrolysis of organic biomass under limited oxygen, was used as a partial replacement of cement [23]. In this study, the replacement of cement with biochar at different mixes. The use of biochar contributes to carbon sequestration, improves sustainability, and may enhance the microstructure of concrete by filling pores.

Image source: https://www.wfpa.org/news-resources/blog/6853/

Fig. 2: Biochar

- Water

Clean potable water free from impurities such as oil, acid, and organic matter was used for mixing and curing. The water–cement ratio was maintained as per the M30 mix design to ensure proper workability and strength. Water conforming to IS 456:2000 was used throughout the experiment.

2.2 MIX DESIGN

The mix design for the study was developed to produce concrete M30 possessing high strength and durability. The selected mix proportion was 1:2:2.71:0.45, corresponding to cement: fine aggregate: coarse aggregate: water. This study focuses on assessing the mechanical and durability performance of concrete incorporating biochar (0%, 2%,4% and 6%) and steel fibres (1%), aiming to develop a low-carbon, high-performance concrete mix suitable for sustainable construction. The carefully designed mix provides workability adequate for placing and compaction, ensures good distribution of steel fibre and yields high strength and enhanced durability.

2.3CASTING OF SPECIMEN

Casting of specimens was carried out in a systematic manner to ensure uniformity and accuracy of results. Initially, the standard moulds (cubes, cylinders, and prisms) were thoroughly cleaned to remove dust and old mortar, and a thin layer of oil was applied on the inner surfaces to prevent the sticking of concrete. The moulds were then assembled properly and placed on a level, rigid surface.

Freshly prepared concrete was filled into the moulds in three equal layers. Each layer was compacted either by tamping with a standard tamping rod or by using a vibration table to eliminate air voids and ensure proper compaction. Care was taken to distribute the concrete evenly and avoid segregation. After placing the final layer, the top surface was levelled using a trowel and finished smoothly to obtain a uniform surface.

The moulds were then covered to prevent moisture loss and kept undisturbed at room temperature for about 24 hours. After this initial setting period, the specimens were carefully demoulded without causing any damage. The demoulded specimens were immediately transferred to a curing tank filled with clean water and maintained at standard temperature. The specimens were cured for specified periods of 7 and 28 days before being taken out for strength testing.

Fig. 3: Mixing of concrete

Fig. 4: Casting of Beam

Fig. 5: Casting of Cylinder

Fig. 6: Casting of Cube

2.4TESTS PERFORMED

An experimental study is conducted to investigate the properties of cement-replaced biochar concretes. A series of compressive strength tests, split tensile strength test, flexural strength test, slump cone test, compaction factor test (workability) were performed on concrete.

2.4.1 Compressive Strength Test

Compressive strength test of concrete for 7 and 28 days was carried out to determine the load-carrying capacity of concrete at different curing periods. It indicated the strength development of concrete with time and was one of the most important properties in structural design. In this procedure, concrete specimens, usually cubes of standard size (150 mm × 150 mm × 150 mm), were cast using the prepared mix and compacted properly. After 24 hours, the specimens were demoulded and cured in water for 7 days and 28 days, respectively. At the end of the curing period, the specimens were removed from water, surface dried, and placed in a compression testing machine. The load was then applied gradually and uniformly until the specimen failed. The maximum load at failure was recorded, and the compressive strength was calculated by dividing the load by the cross-sectional area of the specimen. The test was repeated for multiple specimens, and the average value was taken as the compressive strength of concrete at 7 and 28 days.

Fig. 7: Test Set Up for Testing Compressive Strength (Cube)

2.4.2 Split Tensile Strength Test

Split tensile strength test of concrete at 28 days was carried out to determine the tensile strength of concrete, which indicated its resistance to cracking. In this procedure, cylindrical specimens of standard size (usually 150 mm diameter and 300 mm length) were cast and properly compacted. After 24 hours, the specimens were demoulded and cured in water for 28 days. At the end of the curing period, the specimens were removed, surface dried, and placed horizontally between the loading platens of a compression testing machine. A uniform load was applied along the length of the cylinder until failure occurred due to splitting. The maximum load at failure was recorded, and the split tensile strength was calculated using the standard formula. The average value of the test results was taken as the 28-day split tensile strength of concrete.

Fig.8: Test Set Up for Split Tensile Strength (Cylinder)

2.4.3 Flexural Strength Test

Flexural strength test of concrete at 28 days was carried out to determine the ability of concrete to resist bending stresses and cracking under load. In this procedure, beam specimens of size 500 mm × 100 mm × 100 mm were cast using the prepared concrete mix and properly compacted to remove air voids. After 24 hours, the specimens were demoulded and cured in water for 28 days. At the end of the curing period, the specimens were removed from water and surface dried. The beam was then placed on supporting rollers in a flexural testing machine, and load was applied either at the centre or at two points (third-point loading) gradually until failure occurred. The maximum load at failure was recorded, and the flexural strength was calculated using the standard formula. The result represented the bending strength of concrete at 28 days and indicated its performance under flexural loading conditions.

Fig.9: Test Set Up for Flexural Strength (Beam)

2.4.4 Slump Cone Test

A slump cone test was carried out to determine the workability and consistency of fresh concrete. It indicated the ease with which concrete could be mixed, placed, and compacted. In this procedure, a slump cone mould was placed on a flat, non-absorbent surface and held firmly in position. Freshly prepared concrete was filled into the cone in three equal layers, and each layer was tamped with a standard tamping rod by giving 25 blows. After filling the cone completely, the top surface was levelled, and the cone was carefully lifted vertically upward. The concrete then subsided or slumped. A frustum-shaped cone (300mm high) is filled in three layers, each tamped 25 times. The cone is lifted vertically, and the reduction in height (slump) is measured to assess consistency. The difference between the original height of the cone and the height of the slumped concrete was measured and recorded as the slump value. This value indicated the workability of the concrete, with higher slump values representing higher workability. True slump shows uniform settlement while retaining shape, shear slump indicates sideways slipping due to poor cohesion, and collapse slump represents complete failure caused by an excessively high water-cement ratio.

Fig. 10: Test Set Up for Slump Cone Test

2.4.5 Compaction Factor Test

A compaction factor test was carried out to determine the workability of fresh concrete, especially for mixes with low workability where the slump test was not suitable. It measured the degree of compaction achieved by a standard amount of work. In this procedure, the compaction factor apparatus, consisting of two hoppers and a cylinder, was used. Fresh concrete was placed in the upper hopper without compaction, and the trap door was opened to allow the concrete to fall into the lower hopper. The lower hopper door was then opened, allowing the concrete to fall into the cylinder. The excess concrete was struck off, and the weight of partially compacted concrete was recorded. The cylinder was then refilled with the same concrete in layers with full compaction, and the weight of fully compacted concrete was noted. The compaction factor was calculated as the ratio of the weight of partially compacted concrete to the weight of fully compacted concrete. This value indicated the workability of the concrete, with higher values representing better workability

Fig. 11: Test Set Up for Compaction Factor Test

2.4.6 Cradle Life Cycle Method

The cradle-to-grave Life Cycle Assessment (LCA) method in this study was used to evaluate the environmental impact of concrete mixes up to the production stage. The quantities of materials such as cement, biochar, aggregates, and steel fibres used in each mix were calculated. Emission factors for each material were collected from standard literature sources. The embodied carbon for each component was determined by multiplying the material quantity by its respective emission factor. These values were then summed to obtain the total carbon footprint of each concrete mix. Finally, the carbon emissions of all mixes were compared with their strength results to identify the most sustainable and efficient mix.

2.4.7 Preliminary Tests

Preliminary tests were conducted on the constituent materials before the mix design to determine their suitability and ensure quality control of the concrete. These tests included evaluation of properties such as specific gravity, particle size distribution, bulk density, and moisture content for both fine and coarse aggregates, along with basic characterisation of the binder and alkaline activator. The results of these tests helped in understanding the physical and mechanical properties of the materials, enabling accurate proportioning and ensuring that the concrete mix would achieve the desired strength, workability, and durability.

3 RESULT

3.1 Preliminary Test

Table 1: preliminary test values

Test	Obtained Values	Inference
Fineness of cement	7%	The test result obtained is 7%. Since this value is less than the standard permissible limit of 10%, the cement satisfies the fineness requirement. Therefore, the tested cement is sufficiently fine and is suitable for use in construction.
Consistency of Standard Cement Paste	33.5%	The penetration value lies between 5 mm and 7mm
Initial Setting Time of Cement	75 min	This value indicates the time taken for the cement paste to begin losing its plasticity after the addition of water. Since the obtained initial setting time is greater than the minimum requirement of 30 minutes as per standard specifications, the cement satisfies the standard limits.
Specific Gravity of Cement	3.10.	This value represents the ratio of the weight of cement to the weight of an equal volume of water. The obtained result is close to the standard value of 3.15, indicating that the cement is of good quality and free from excessive impurities or voids. Therefore, it can be concluded that the cement is suitable for use in construction.

Particle Size Distribution of Fine Aggregates	Fineness modulus =2.946 Uniformity co-efficient = 2.63 Effective size = 0.19	The obtained fineness modulus of 2.946 indicates that the sand sample falls under the category of medium to coarse sand.
Bulking of fine aggregate	Moisture content at maximum bulking = 9% Moisture content at zero bulking= 19% Percentage of maximum bulking= 45%	Bulking peaked at 45% at 9% moisture content, more than the standard range of 4-6%. Hence, weigh batching or bulking correction is necessary for the mix design.
Specific Gravity of Fine Aggregate	2.46	The specific gravity of fine aggregate used is 2.46, which is lower than the standard value of 2.60-2.70. This indicates the material is comparatively light and porous.
Particle Size Distribution of Fine Aggregates	Fineness modulus =10.185 Uniformity co-efficient = 1.466 Effective size = 15	The crushing value is within the permissible limit, showing adequate strength and suitability for reinforced geopolymer concrete beams
Bulk Density, Void Ratio, Porosity	Bulk Density=1.607 Void Ratio = 0.738 Porosity= 0.424	These values were calculated using the bulk density and specific gravity of the aggregate. These properties were useful in concrete mix design, as they influenced the workability, strength, and durability of concrete.
Specific gravity of Coarse aggregate	2.73	The results obtained for the specific gravity of coarse aggregate indicated that the specific gravity was 2.945 and the apparent specific gravity was 3.0, which are within the typical range for good quality aggregates and indicate high density and strength. However, the water absorption was found to be 61.3%.
Specific Gravity Test on Biochar	1.58	This relatively low value indicates that biochar is a lightweight and porous material when compared to conventional aggregates, which makes it suitable for applications where reduced density and improved soil or material properties are desired.

	6.7%	This value indicates that the biochar particles are sufficiently fine, providing a higher surface area for better interaction with cement. Since the obtained residue falls within acceptable limits, the biochar is suitable for use as a partial replacement material in concrete, thereby improving bonding and overall performance.

3.2Compaction Factor Test

Table 2: Compaction Factor Test

Mixtures	Compaction factor	Inference
0% BC & 1% SF	0.912	Plastic
2% BC & 1% SF	0.882	Stiff Plastic
4% BC & 1% SF	0.850	Stiff Plastic
6% BC & 1% SF	0.732	Stiff

3.3Slump Cone Test

Table 3: Slump cone test

Mixture	Slump (mm)	Inference
0% BC & 1% SF	55	Plastic
2% BC & 1% SF	15	Stiff Plastic
4% BC & 1% SF	23	Stiff Plastic
6% BC & 1% SF	27	Stiff

The table shows the variation of the slump cone with increasing percentage of biochar in concrete.

3.4 Split Tensile Strength Test

Table 4: Split Tensile Strength Test

Specimen	Split Tensile Strength (N/mm^2)
Cylinder (0% BC &1% SF	2.82
Cylinder (2% BC &1% SF	3.20
Cylinder (4% BC &1% SF	3.71
Cylinder (6% BC &1% SF	3.53

The table shows the variation of split tensile strength with increasing percentage of biochar in concrete.

4 CONCLUSIONS

In this study, concrete mixes were prepared with 0%, 2%, 4%, and 6% biochar as partial replacement of cement, along with a constant addition of 1% steel fibre throughout all mixes. Based on the experimental results, it is observed that the inclusion of biochar slightly improves the workability of concrete, as indicated by the increase in slump values and compaction factor, though the mixes generally remained in the stiff-to-stiff plastic range.

The strength characteristics showed that the addition of biochar, combined with steel fibre, provides satisfactory performance in compressive, flexural, and split tensile strength. An optimum performance was observed around 4% biochar, where strength is maintained or slightly improved due to better particle packing and fibre reinforcement, while higher percentages (6%) may show a marginal reduction but remain within acceptable limits. The presence of steel fibres significantly enhanced tensile and flexural behaviour by improving crack resistance and ductility.

The cradle life cycle assessment revealed a substantial reduction in embodied CO_2 emissions with increasing biochar content. While the control mix exhibited the highest emissions, the 4% and 6% biochar mixes showed carbon-neutral to carbon-negative behaviour, confirming effective carbon sequestration.

Overall, the study concludes that the use of 4% biochar with 1% steel fibre is the optimum combination, achieving a balance between mechanical performance, workability, and environmental sustainability. This approach offers a promising solution for developing eco-friendly, carbon-negative concrete for future construction applications. This study assessed only material-based embodied CO_2 using standard emission factors. Transportation, construction, and end-of-life stages were excluded. Future work may include a full life cycle assessment.

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