Journal of Material Cycles and Waste Management (2024) 26:936–945
https://doi.org/10.1007/s10163-023-01871-w

ORIGINAL ARTICLE

Impact resistance and durability of natural fibre reinforced concrete pavement and partial replacement with steel slag aggregate

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Received: 7 April 2022 / Accepted: 30 November 2023 / Published online: 9 January 2024

Abstract

Steel slag is a product of industrial waste and such has been used as alternative aggregate materials in concrete production. Coconut fibre is readily available in tropical countries such as Nigeria. This paper focussed on using steel slag waste to replace granite at 10, 20, and 30% with the addition of coconut fibres of 40 mm average length added to the concrete at 0.3 and 0.6% of cement weight. Concrete samples of 40 MPa targeted strength were prepared with mix ratio of 1:1.3:2.2 and a water–cement ratio of 0.4, which were cured for 14, 28, 56, and 90 days and tested for impact strength, energy absorption from cracking, mechanical strengths, and durability. The impact resistance of the modified specimens was greater than the control specimens because the number of blows and potential energy needed to crack the slabs to cause ultimate destruction was higher in the modified concrete samples. The optimum compressive, split tensile strengths and sulphate attack were observed at 20% partial replacement of steel slag with granite at 0.3% coconut fibre binder weight which performed better than the control, indicating the durability of concrete infused with steel slag aggregate and natural fibres.

Keywords Steel slag · Coconut fibre · Concrete · Crack width · Durability · Impact strength

Abbreviations

FUNAAB	Federal university of agriculture, Abeokuta
CTRL	Control samples
A10	Concrete samples with 10% steel slag and 0.3% fibre
A20	Concrete samples with 20% steel slag and 0.3% fibre
A30	Concrete samples with 30% steel slag and 0.3% fibre
B10	Concrete samples with 10% steel slag and 0.6% fibre
B20	Concrete samples with 20% steel slag and 0.6% fibre
B30	Concrete samples with 30% steel slag and 0.6% fibre
ASTM	American society for testing and materials

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Introduction

Normal concrete slabs have low strength and low strain characteristics but these structural properties can be improved with the addition of fibres, thus reducing the thickness and enhancing their engineering characteristics [1–8]. Unreinforced cementitious materials are characterised by low tensile strength, low fracture toughness, and low tensile strain capacities. Different fibres are used in concrete: glass fibre, steel fibre, polymeric fibre, and natural fibres. Improvement in the material behaviour of fibre-reinforced concrete depends on the dosage and characteristics of the fibres used.

Natural fibres possess many advantages over synthetic fibres, including low cost, low density, non-abrasive, good thermal properties, enhanced energy recovery, and biodegradability [1, 9].

Structures experience impact loading, especially structures that are designed to experience impact loading during their design examples of such structures are offshore facilities, piles, and structures in seismic areas. Some other examples of structural and non-structural infrastructure subjected to high loads are hydraulic structures, airport and highway paving and overlays, industrial floors, refractory concrete, bridge decks, concrete linings and coverings, and thin-shell structures [2]. Civil infrastructure is exposed to a variety of extreme environmental events and/or dynamic loads hence there is a need to design them to resist seismic, impact, and blast loading to enhance public safety [10]. Many researchers [1–3] have investigated the impact strength characteristics of fibre reinforced composites and repeated impact i.e. the dropping weight test has been extensively used to evaluate it. Ramakrishna and Sundararajan [1] tested four natural fibres (coir, sisal, jute, and hibiscus cannabis) with four different fibre contents and three fibre lengths. It was reported that the impact strength of mortars with fibre reinforcement was higher than those without fibre reinforcement and that the fibre increased the impact resistance by 3–18 times more than that of the reference mortar slab. The mechanical performance of cement composites reinforced with sisal, banana, and eucalyptus fibres was compared [11]. It was found that those cement composites reinforced by sisal and banana fibres with a length of 1.65 or 1.95 mm exhibited more stable fracture characteristics than those reinforced with eucalyptus fibres with a length of 0.66 mm. Xiangming et al. [3] investigated fracture and impact properties of short discrete jute fibre-reinforced cementitious composites (JFRCC). The impact resistance of JFRCC was examined on mortar panels with dimensions of $200 \times 200 \times 20$ mm^3 at 7, 14, and 28 days through repeated dropping weight tests. The impact test indicated that JFRCC mortar panels with pulverised fly ash/Portland cement matrix possessed higher impact resistance, absorbed more impact energy, and survived more impact blows upon failure than those with ground granulated blast furnace slag/Portland cement matrix at the ages of 14 and 28 days.

Strength and durability are regarded as the most important criteria in concrete structure designs. The durability of a concrete element depends greatly on the ability of a fluid to penetrate the concrete's microstructure allowing the introduction of molecules such as carbon dioxide, chloride ions, etc. which react and destroy its chemical stability. It is known that this movement occurs in three ways: permeation, capillarity, and, diffusion [12]. The durability of concrete may be referred to as the ability to resist quality degradation when exposed to environments that cause deleterious effects on the concrete [8, 13, 14]. Chloride ions in concrete microstructure and carbonation are the main factors reducing concrete durability as a result of their movement due to their concentration gradient within the concrete microstructure [12, 15–17]. Sulphate attack is the term used to describe a series of chemical reactions between sulphate ions and the components of hardened concrete due to exposure to sulphate and moisture. Past research activities [1, 8, 11, 22, 40] on fibre-reinforced concrete have focussed on the use of virgin aggregates and natural fibres on impact resistance hence, this study focuses on the impact resistance and durability of concrete pavement reinforced with coconut fibres with a percentage replacement of coarse aggregate with steel slag. Research recently explored the possibility of granulated slag aggregate in concrete where durability was investigated concerning moisture, freezing and leaching [18, 19]. The mechanical properties of concrete were investigated by measuring parameters such as compressive, flexural and split tensile strengths as well as drop weight impact, energy absorption from cracking and durability.

Materials and methods

Materials

The materials used for this research include conventional coarse aggregates (granite of size 19 mm), fine aggregate (river sand passed through sieve no 200), Portland limestone cement of Type 1, water, steel slag, and natural coconut fibres. The steel slag aggregate was obtained from African steel, Ikorodu. The natural coconut fibre was obtained from Iyesi-Otta in Ogun state and was processed at the Federal University of Agriculture, Abeokuta (FUNAAB) in Nigeria.

Preparation of specimens

The natural coconut fibres were separated from their husk and were soaked for forty-eight hours in 0.1 M of NaOH solution mixed with tap water at room temperature. The fibres were rinsed in clean water and dried in an oven at 80 °C until an equilibrium moisture content was achieved. This was done to remove the leachate in the fibres, conserve its durability, improve interfacial bonding, and facilitate efficient coupling between the fibre and the resulting matrix [20–22]. The steel slag was crushed into the desired aggregate size of 19 mm by manual means. Laboratory tests such as specific gravity, sieve analysis, water absorption, bulk density, fineness modulus, flakiness, aggregate impact, and crushing values were carried out on the granite, sand, and steel slag which were by relevant specifications. The physical and mechanical properties of the coconut fibre were also examined. Mix proportion of the concrete was done according to the ASTM method with a targeted strength characteristic of 40 MPa at 28 days and a water-cement ratio of 0.4.

The fibres of 40 mm average length were added to the concrete at 0.3% and 0.6% by cement weight according to the work of Abiola et al. and other researchers [8, 9, 23–25] whilst steel slag was used to partially replace the coarse aggregates in parts of 10, 20, and 30% based on the total weight of coarse aggregate. Each batch with coconut fibre and steel slag was named according to their coconut fibre content and steel slag content. Samples with 0.3% coconut fibre and 10, 20, and 30% steel slag were identified as A10, A20, and A30, respectively, whilst samples with 0.6%

coconut fibre and 10, 20, and 30% steel slag were identified as B10, B20, and B30, respectively. The control specimen containing just conventional aggregates was denoted by CTRL. The amount of all materials based on 1 m^3 of the total mix was produced and after 24 h, the moulds were removed and the specimens were placed in a water tank for 14, 28, 56, and 90 days.

Mix design of concrete

The proportion of each material by mass to the target compressive strength of 40 MPa and a mix design of 1: 1.3: 2.2 of cement, river sand, and granite, respectively are presented in Table 1. Seven mixes were prepared with 0.3 and 0.6% of coconut fibres by cement weight, and coarse aggregate was replaced with 10, 20, and 30% steel slag.

Preliminary tests of materials

The result of the preliminary test on materials used for this research is shown in Table 2. The specific gravity of river sand, granite, and steel slag are 2.70, 2.69, and 3.25, with their water absorption as 8.32, 0.54, and 2.79%, respectively.

Mechanical strength tests

The compressive, flexural, and split tensile strengths of the resulting concrete were determined at 14, 28, 56, and 90 days whilst the impact under drop weight test was carried out at 28 days and 56 days. The properties of the modified concrete specimens were compared to the properties of the control specimens labelled CTRL. The tests were carried out according to American Society for Testing and Materials (ASTM) specifications.

Compressive strength test

The compressive strength test was performed for 84 standard test cylinders following ASTM C39 [31]. This test was done to determine the value of uniaxial compressive stress at which the material failed. This test was carried out using the Universal Testing Machine.

Split tensile strength test

The split tensile strength test was carried out on 52 test cylinders following ASTM C496 [31] using a Universal Testing Machine. The formula for calculating the split tensile strength is given as illustrated in Eq. 1:

$$S = \frac{2P}{\pi Ld} \tag{1}$$

where S= Split tensile strength
P = collapse load or force
L = length of the specimen

Table 1 Mix proportion of concrete mixes

Sample	Mass of granite (kg)	Mass of river sand (kg)	Mass of cement (kg)	Mass of steel slag (kg)	Mass of coconut fiber (kg)	Mass of water (kg)
CTRL	739	437	336	–	–	134
A10	665	437	336	74	1.008	134
A20	591	437	336	148	1.008	134
A30	517	437	336	222	1.008	134
B10	665	437	336	74	2.016	134
B20	591	437	336	148	2.016	134
B30	222	437	336	222	2.016	134

Table 2 Result of preliminary test on materials

Properties	Specifications	River sand	Granite	Steel slag	Coconut fiber
Specific gravity	ASTM D854 [26]	2.70	2.69	3.25	–
Water absorption (%)	ASTM C127 [27]	8.32	0.54	2.79	13.00
Loose bulk density (kg/m^3)	ASTM C29 [28]	1243.56	1389.71	1425.53	–
Particle density (g/m^3)		2.60	2.60	2.85	1.30
Compacted bulk density(kg/m^3)		1512.34	1678.52	1775.33	–
Fineness modulus	ASTM C 33 [29]	2.56	–	–	–
Aggregate impact value	BS 812–112:1990 [30]	–	11.59	17.32	–
Tensile strength (MPa)		–	–	–	167.00

d = diameter of the cross-section of the cylindrical specimen

Flexural strength test

The resistance of an unreinforced concrete beam or slab to failure by bending, which is also known as flexural strength is one of the ways of measuring the tensile strength of concrete. This property was measured by loading $500mm \times 100mm \times 100mm$ concrete beams with a span length of at least three times the depth following ASTM C78 [32]. Universal Testing Machine was used to carry out the test on the specimens whilst the modulus of rupture of the specimens was calculated using the formula illustrated in Eq. 2:

$$\delta = \frac{3PL}{2\pi bd^2} \quad (2)$$

where δ = modulus of rupture,

P= applied load in newton,

L, b and d= span/length, breadth and depth of specimen, respectively.

Cracking and drop weight impact test

The cracking of the slab specimens was carried out by dropping a 4.5 kg hammer at a uniform height of 450 mm on the centre of the slab as recommended by ACI 544.2R-89 (1989) [33]. The number of blows required for the initiation of the first and ultimate cracks was observed and recorded. The total computed impact energy is assumed to be fully absorbed by the slab. The initial and final impact energy absorbed under the impact load was used as a measure of their impact resistance and calculated using the relation illustrated in Eq. 3:

$$E = N * mgh \quad (3)$$

where E= Impact Energy in Joules

m= mass of rammer

g= acceleration due to gravity

h= height of drop the of hammer

The residual impact strength ratio, I_{RS}, was also determined using formula illustrated in Eq. 4:

$$I_{RS} = \frac{Energy\ absorbed\ at\ ultimate\ failure}{Energy\ absorbed\ at\ initiation\ of\ first\ crack} \quad (4)$$

Durability tests

Sulphate attack in concrete

The sulphate attack on concrete was carried out by immersing the concrete specimen (cylindrical) in 5% sodium sulphate solution (Na_2SO_4) for several days of curing (14, 28, 56, and 90 days) as shown in Fig. 1. This testing procedure indicated the performance of particular concrete mixes to sulphate attack in concrete. The degree of the attack of sulphate was evaluated by measuring the expansion of concrete cylinders, compressive strength and, weight losses of the specimens at 14, 28, 56 and 90 days, respectively.

Carbonation depth of concrete

This was carried out according to the method of the phenolphthalein test for measuring carbonation depth determined by RILEM CPC—18. Phenolphthalein was prepared by dissolving the solution in ethyl alcohol and the resulting solution was sprayed onto the concrete surface, which has been thoroughly cleaned of dust, and loose concrete particles. The phenolphthalein worked as an indicator; it turned red when the pH value exceeded 9.5 to show the alkalinity of the concrete and it was colourless when carbonation had taken place (Fig. 2).

Results and discussion

Mechanical strength test results

Compressive strength tests

The result of the compressive strength tests of the concrete specimens as presented in Fig. 3 showed that all specimens containing 0.3% fibre reached and exceeded the target strength at 28 days but B10, B20, and B30 specimens did not. There was an increase in strength of 8.3 and 21.6% for A10 and A20 respectively when compared to the control (CTRL) whilst A30 showed a decrease of 9.9%. It was

Fig. 1 Immersion of concrete in sulphate solution

Fig. 2 Carbonation depth of concrete using phenolphthalein and ethanol

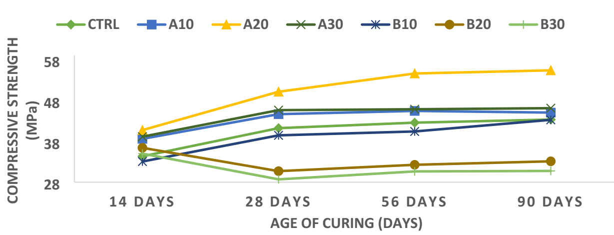

Fig. 3 Compressive strength test results of concrete specimens

observed that increasing the fibre to 0.6%, a decrease of 4.3, 25.5, and 30.4% in compressive strength for B10, B20 and B30 respectively. The interaction of the cement paste with the coconut fibre may have caused the failure of the concrete at lower compressive strength as well as compaction and lack of workability at larger doses of the fibre (> 0.5%) as reported by Ede and Agbede [42]; Rumbayan and Ticoalu [43]. As suggested by Suleyman, Diri, & Mermerdas [34] that the particle density of the fibre is low compared to the aggregate could result in a decrease in the compressive strength. Moreover, the compressive strength of the concrete samples still increased considerably after the 28th-day curing. Thus, concrete mixtures with higher compressive strength were stronger and more durable than the others with lower compressive strengths as reported in the literature [35–37].

Split tensile strength tests

The result of the split tensile strength tests of the concrete specimens as presented in Fig. 4 revealed that specimens A10, A20, A30, and B10 showed higher split tensile strength across all testing days compared to the control specimen. Generally, the concrete with steel slag showed higher strength than the control both in compression and tension. This can be attributed to the pozzolanic nature of steel slag which contributed to the increase. However, the fibre inclusion of 0.3% increase the split tensile strength of the concrete. Moreover, the opposite was the case for specimens B20 and B30 as the specimens showed lower split tensile strength compared to the control. The increase in split tensile strength of B10, A30, A10 and A20 at 28 days of curing were 6.6, 11.4, 30.7, and 33.8%, respectively when compared with the control specimen. At the 90th day of curing, the tensile strength of all the tested cases increases with

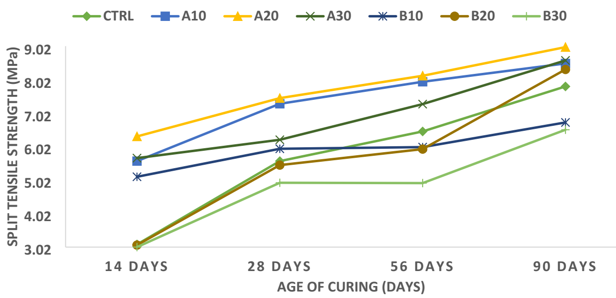

Fig. 4 Split tensile test of the concrete at 14, 28, 56, and 90 days

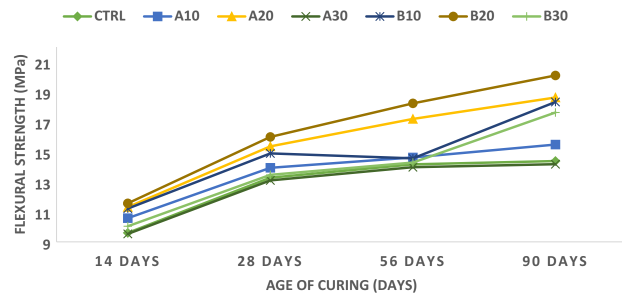

Fig. 5 Flexural strength test of the concrete at 14, 28, 56, and 90 days

A20 having the highest. It is, therefore, safe to say that the replacement of steel slag aggregates up to 30% with 0.3% fibre definitely improved and increased split tensile strength. This result further collaborates what other researchers have obtained that, steel slag aggregate and natural fibres can increase the resistance of concrete to bending or cracking under tension [38–40]. Increasing the fibre content has a direct influence on the strength characteristics which invariably reduces its tensile strength as earlier stated above.

Flexural strength tests

The flexural strength test results as presented in Fig. 5 showed that only specimen A30 had the lowest flexural strength value across all the testing days and was lower than the control specimen value. Hence the infusion of natural fibres and steel slag aggregate at A10, A20, B10, B20, and B30 surely help in improving the resistance to bending or tensile forces of concrete which is consistent with the results of Shadheer et al. [40].

Cracking and impact absorption

The results of the crack width of slabs presented in Table 3 showed that there was a considerable decrease in crack width as the percentage of natural fibres increased. The addition of steel slag aggregates only marginally decreased the crack width. As shown in Table 4, the impact resistance of the modified specimens was greater than the control specimens since the number of blows and potential energy needed for the first crack and ultimate crack was higher in the modified concrete samples than in the control samples. The peak energy that caused the ultimate crack was determined to be 198.65 Joules (specimen B30) and the least is 59.60 Joules (CTRL specimen). At 28 days, only specimens A10 and B10 had greater I_{rs} results (1.75 and 1.80 respectively) which were even higher than the CTRL specimens with a value of 1.67. However, at 56 days, only specimen A20 gave the highest I_{rs} result when compared to the CTRL and other specimens. The bar chart in Fig. 6 presents the initial and final energy absorbed the specimens. From observation, the impact resistance of the modified specimens showed an increasing trend as the fibre content increases Crack width of slabs at 28 days and 56 days.

Durability tests

Carbonation depth

The carbonation depth was measured at ages 28, 56, and 90 days as shown in Fig. 7. It can be seen that the carbonation depth increased as the age of curing increased and higher CO_2 concentration. Concrete specimens of A samples were marginally lower than those of B samples. The lowest carbonation depth occurred in the A30 sample and the peak carbonation depth occurred in the control sample where there was no slag or fibre addition. Blast furnace slag addition resulted in lower carbonation depth as seen from the results because the pozzolanic reaction and filling effect were beneficial in minimising the pore size and volume which led to a reduced carbonation rate. Ramli [8] reported that the carbonation depths recorded increased with the fibre content and the results coincided with the above inference. The difference was the variability added by the use of steel slag aggregate.

Table 3 Crack width of slabs at 28 days and 56 days

Slab Samples	Crack width (mm)			
	28 Days		56 Days	
	Longitudinal	Transverse	Longitudinal	Transverse
CTRL	7	6	5	4
A10	5	4	4	3
A20	4	4	3	2.5
A30	3.5	3	3	2.5
B10	3	2	2	2
B20	2	2	2	1.5
B30	3	3	2	1.5

Table 4 Energy absorbed by slab specimens

Sample	28 Days					56 Days				
	No of blows	Initial energy absorbed (Joules)	No of blows	Final energy absorbed (Joules)	I_{rs}	No of blows	Initial energy absorbed (Joules)	No of blows	Final energy absorbed (Joules)	I_{rs}
CTRL	3	59.6	5	99.33	1.67	4	79.46	7	139.06	1.75
A10	4	79.46	7	139.00	1.75	5	99.33	8	168.52	1.70
A20	5	99.33	8	158.92	1.60	5	99.30	9	178.79	1.80
A30	5	99.33	8	158.92	1.60	6	119.19	9	178.79	1.50
B10	5	99.33	9	178.79	1.80	6	119.19	9	178.79	1.50
B20	6	119.91	9	178.79	1.49	7	139.06	10	198.65	1.43
B30	6	119.91	9	178.79	1.49	7	139.06	10	198.65	1.43

Sulphate attack

Exposure of cement concrete to sulphate salt caused expansion, cracking, spalling, a loss of mass and strength of the concrete. Sulphate attack on Portland limestone cement is characterised by sulphate ions with cement hydration products. From the results in Fig. 8, the behaviour of concrete specimens with natural fibre and steel slag different from the control specimens with Portland Limestone Cement. The compressive strength of the specimens cured in Na_2SO_4 solution is generally lesser than the specimens cured in portable water. There was also weight loss in the concrete specimens immersed in Na_2SO_4 solution. The strength losses increase with curing days for control and A10, whereas for the remaining specimens the reverse was the case. Figure 8 also showed an increase in percentage loss from 12% to 13.82% for control samples, this collaborate with Sivarja et al. that natural fibre reinforced concrete are less prone to sulphate attack [41]. The percentage of loss was reduced considerably for the remaining samples from A10-B30 (Table 5). This showed that the addition of coconut fibre and steel slag improved the durability of the concrete.

Conclusion

This research was aimed at partially substituting granite with steel slag at 10, 20, and 30% with the addition of coconut fibres of 40 mm average length added to the concrete at 0.3 and 0.6% of its cement weight. Concrete samples of 40 MPa targeted strength were prepared with a mix ratio of 1:1.3:2.2 and a water-cement ratio of 0.4, which were cured for 14, 28, 56, and 90 days and tested for impact strength, energy absorption from cracking, mechanical strengths, and durability. The following conclusions were made from the above results:

- All specimens with 0.3% fibre content reached and exceeded the target compressive strength at 28 days whilst specimens with 0.6% fibre did not.
- It was observed that specimens A10, A20, A30, and B10 showed higher split tensile strength across all testing days compared to the control specimen.
- The flexural strength showed that the blend of natural fibres at 0.3% and steel slag aggregate at 10 and 20% as well as a blend of natural fibres at 0.6% and steel slag aggregate at 10, 20, and 30% in concrete improved the resistance to bending or tensile forces of concrete.
- The impact resistance of the modified specimens was greater than the control specimen. This can be used as sustainable eco-green materials for various potential concrete pavements.

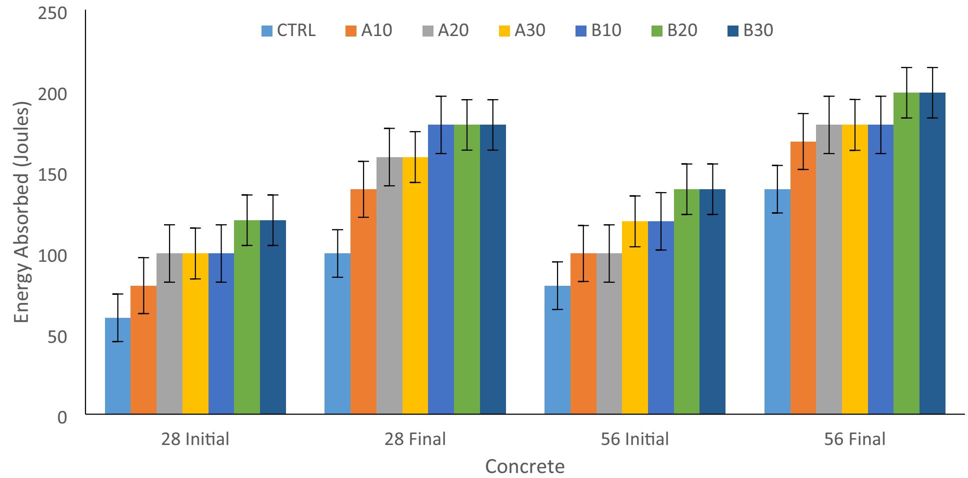

Fig. 6 Initial and Final Energy absorbed by concrete samples

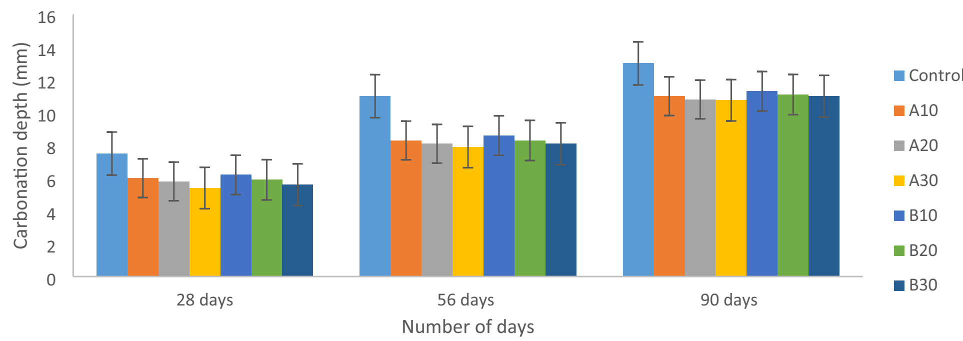

Fig. 7 Carbonation depth of concrete samples

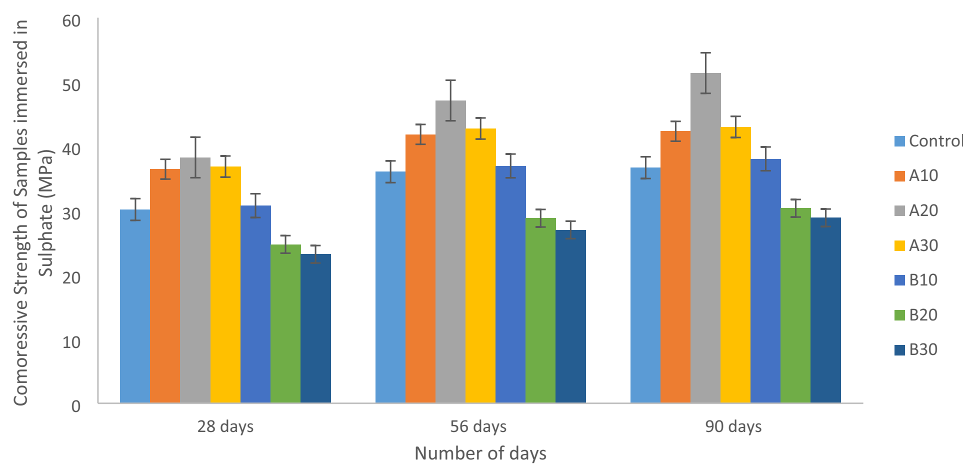

Fig. 8 Compressive strength of concrete samples immersed in sulphate (MPa)

- Variations in results were observed in terms of residual impact strength ratio for both specimens A and B, but the greater residual impact strength ratio fibre-reinforced concrete was higher than the control specimen.
- The carbonation depth increases as the age of curing increases. Specimens with 0.3% fibre content have the lowest value for all the days considered
- Sulphate attack on concrete reduced with an increase in steel slag aggregate and natural fibre, indicating the durability of concrete infused with steel slag aggregate and natural fibres. This suggest the possibility of use in the port to mitigate the negative impact of seawater attack on concrete.
- The results of compressive strength for 0.3% fibre can be used effectively to design concrete pavement for short term duration whilst further work for long term duration is proposed

Table 5 Percentage loss of concrete strength immersed in sulphate

Sample	Percentage loss in strength 28 days	56 days	90 days
Control	12.16	12.57	13.82
A10	5.61	6.22	6.81
A20	6.07	5.97	5.82
A30	6.31	6.24	6.16
B10	6.57	6.37	6.05
B20	6.33	6.18	5.89
B30	7.16	5.95	5.75

Author contributions OS and OA analysed and interpreted the data obtained from the laboratory tests. OS and DI performed the laboratory tests. OS, OA, and UT were major contributors to writing the manuscript. All authors read and approved the final manuscript.

Funding Personal funds from the authors were used to carry out this research.

Data availability The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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