Journal of Engineering Science and Technology
Vol. 14, No. 3 (2019) 1482 - 1496

MECHANICAL AND DURABILITY PROPERTIES OF COIR FIBRE REINFORCED CONCRETE

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Abstract

The need to use sustainable materials for construction is growing. This study investigated the effect of incorporating 0.5 and 1% coir fibre content on the workability, density, compressive strength, splitting tensile strength, and durability of concrete. The splitting tensile strength was determined at 7, 14 and 28 days while the compressive strength was determined up to 56 days following relevant code procedures. The durability of coir fibre reinforced concrete was investigated by subjecting hardened cube specimens to 1, 3 and 5% magnesium sulphate solutions for 28 and 56 days after curing in water for an initial period of 28 days. The compressive strength loss and mass losses were determined with reference to the control mixes. The incorporation of coir fibre in concrete reduced its workability and seemed to have no effect on the density. Coir fibre slightly improved the compressive and tensile strength of concrete, especially at 0.5% while its resistance to sulphate attack was only improved at 1% coir fibre content.

Keywords: Coir fibre, Compressive strength, Durability, Fibre reinforced concrete, Tensile strength.

1. Introduction

For developing regions in Africa where conventional fibres are elusive, the need to search for similar alternatives cannot be overemphasised. Moreover, some of the natural fibres are waste materials that are left to constitute a menace in the environment where they are dumped. Examples of natural plant fibres are coconut (coir) fibre, bamboo fibre, wood fibre, sisal fibre, elephant grass, etc. [1-3]. For coir fibre that is in abundance in Nigeria, its application for building purposes is in reinforcing roofing materials and celling boards.

Beyond these, the fibre serves as environmental waste. Since cracks in concrete, particularly in foundation slab is a major challenge due to the inherent weakness of concrete in tension, exposing it to deterioration from chemical substances, an investigation into the use of coir fibre in concrete is worthwhile. It is now common knowledge that fibres in concrete generally can enhance its toughness, ductility, shear strength, energy absorption capacity, damage tolerance, stress distribution, volume changes, among others [4, 5].

Concrete is often designed to be adequate in strength and durability. However, incompatibility of the elastic moduli of the aggregate-paste interface leads to stress-strain concentrations [6, 7]. This coupled with creep-fatigue due to sustained loads, give rise to internal disruptions in concrete [8]. Due to these and other factors such as shrinkage, thermal movements and loading conditions, microscopic cracks (2-5 µm) spread and interconnect [6, 7, 9, 10]. With crack propagation, there will be increased transport of the aggressive fluid leading to self-propagated deterioration cracks and expansive disruptions [7]. The incorporation of coir fibre (CF) in the matrix will distribute stress-strain concentrations, bridge internal and expansive disruptions; and limit crack initiation and propagation.

Coir fibres are obtained from the husks of the coconut fruit. The common name, scientific name and plant family of coconut fibre are Coir, Cocos nucifera and Arecaceae (Palm), respectively [11]. There are two types of coconut fibres, brown fibres extracted from matured coconuts and white fibres extracted from immature coconuts [11-13]. Brown fibres are thick, strong and have high abrasion resistance.

White fibres are smoother and finer, but weaker. These types of fibres have different uses depending upon the application requirement. According to Satyanarayana et al. [14] and Munawar et al. [15], coir fibre has the highest toughness out of other natural fibres. Due to environmental sustainability and its abundant sources in Nigeria (especially for rural housing schemes), brown coir fibres were used for this study.

In the present study, varying proportions of discrete brown coir fibres were incorporated in concrete mixes to examine its effect on the compressive strength, tensile strength and resistance to magnesium sulphate. Due to fibre inclusion, the improvement in plain concrete's stress distribution (compressive and tensile strengths) and microstructure by limiting expansive disruption and crack initiation/propagation due to aggressive sulphate ingression by determining deterioration factors in terms of mass loss and compressive strength loss are to be investigated.

2. Materials and methods

2.1. Cement and aggregates

CEM I Ordinary Portland Cement (OPC) of grade 42.5R confirmed to the requirements of BS EN 197-1 [16] was used. Fine sand passed through 4.75 mm to 63 µm sieve sizes while granite of size ranging from 20 mm to 6.3 mm was used. Sieve analyses carried out on the sand and granite show that they complied with the requirements of BS EN 12620 [17]. Table 1 shows the physical properties of the aggregates while Fig. 1 shows the grading curves.

Table 1. Physical properties of aggregates used.

	Specific gravity	Fineness modulus	Coefficient of uniformity (C_u)	Coefficient of curvature (C_c)
Sand	2.65	2.5	6	1
Granite	2.8	7.1	2	1.1

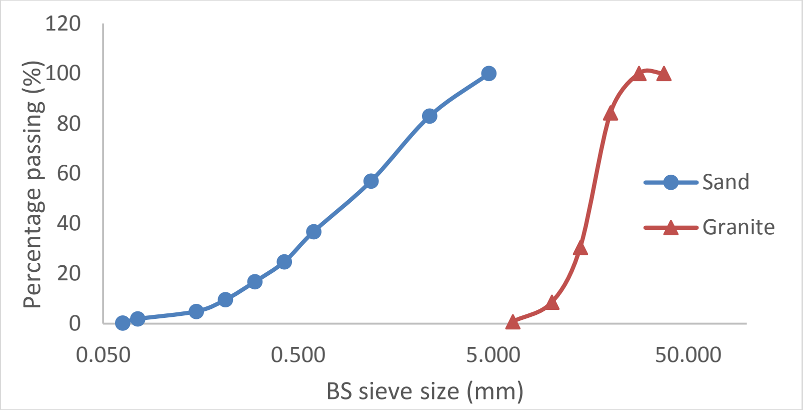

Fig. 1. Grading curves of aggregates used.

2.2. Coir fibre

Coir Fibre (CF) was extracted into strands from its husk using cutlass and knife after which, it was washed thoroughly in warm water and left to dry before cutting into specified dimensions [5]. Figure 2 shows the fibres in the raw and processed states, Table 2 shows the physical properties, while Table 3 shows the typical chemical properties of coir fibre. An extensive study by Yalley and Kwan [18] reported a maximum of 125 aspect ratio for CF in concrete in order to achieve good results.

Table 2. Physical properties of coir fibre.

Properties	Coir fibre
Colour	Brown
Average length (mm)	40
Average diameter (mm)	0.36
Aspect ratio	111

Table 3. Chemical properties of coir fibre.

Items	Percentages
Water soluble	5.25%
Pectin and related compounds	3.00%
Hemicellulose	0.25%
Lignin	45.84%
Cellulose	43.44%
Ash	2.22%

Source: Verma et al. [19].


(a) **(b)**

Fig. 2. Removed coir fibre: (a) Before pre-treatment and sizing, (b) After pre-treatment and cutting to average 40 mm length and diameter of 3.6 µm.

2.3. Concrete mix design

The experimental mix design was in two batches. For the first batch (*A*), concrete mixes of ratio 1:2:3.5 with water-cement (w/c) ratio of 0.55 and coir fibre contents of 0, 0.5, and 1% (by wt. of cement) were produced. Similarly, for the second batch (*B*), concrete mixes of ratio 1:3:5.8 with a water-cement ratio of 0.55 and coir fibre contents of 0 and 1% (by wt. of cement) were produced. Batch *A* specimens were used for compressive and tensile strengths, and durability tests. Batch *B* specimens were used for only compressive and tensile strength tests. The mix of proportions and denotations are given in Table 4. Batches *A* and *B* mix were separate studies formulated to represent structural and non-structural concrete applications respectively but combined for this paper. Therefore, higher inclusion of CF (1%) and 28 days testing were only adopted for Batch *B* (typical of rural housing use).

Table 4. Mix proportion of coir fibre reinforced concrete with water-cement ratio of 0.55.

Batch label	CF (%)	Mix ratio	Cement (kg/m^3)	Water (kg/m^3)	CF (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
***A*0**	0	1:2:3.5	353	194	0	699	1258
***A*1**	0.5				1.765	698	1257
***A*2**	1				3.53	697	1256
***B*0**	0	1:3:5.8	243	133	0	709	1420
***B*1**	1				2.43	708	1417

2.4. Compressive and splitting tensile strength tests

The concrete specimens were prepared and cured according to the requirements of BS EN 12390-2 [20]. Sand and OPC were manually mixed before adding coir fibre; thereafter, thoroughly remixed before granite was added. Slump values of the various mixes were also determined according to BS EN 12350-2 [21]. The concrete was thereafter placed into moulds in three layers; each layer was compacted manually (25 strokes) by a 25 mm compacting steel rod. Concrete specimens of 100 mm cubes were made from the various mixes and demoulded after 24 hours of casting. After demoulding, the specimens from Batch A were cured in water for 7, 14, 28 and 56 days.

After 28 days of water curing, some specimens were transferred to a 100 L magnesium sulphate ($MgSO_4$) solution container for another 28 and 56 days for durability tests. Of all sources of chemical attack, magnesium sulphate is the most detrimental; it attacks all concrete products such as Calcium Silicate Hydrate (CSH), Calcium Aluminate Hydrate (CAH) and Calcium Hydroxide (CH) [22-25], with the known concentrations of the $MgSO_4$ (C_1), volume of solutions to be prepared (V_2) and concentration of solutions needed (C_2), the volume of $MgSO_4$ (V_1) needed to be mixed with the 100 L of water to give a concentration of 1, 3 and 5% were determined. Specimens from Batch B were only cured in water for 7, 14 and 28 days. All curing was by complete immersion and at room temperature. After the specified days of water curing, Batches A and B specimens were tested for compressive and splitting tensile strengths in accordance with the requirements of BS EN 12390-3 [26] and BS EN 12390-6 [27], respectively, using an ELE 2000 kN compression testing machine conforming to BS EN 12390-4 [28]. Three replicates and 100 mm cubes were used for all the tests (compressive, tensile and durability).

2.5. Durability test

For Batch A specimens cured further in $MgSO_4$ after 28 days of water curing, Mass Deterioration Factor (MDF) and compressive Strength Deterioration Factor (SDF) were determined as given in Eqs. 1 and 2 [29, 30].

$$\text{Mass deterioration factor (MDF)} = \frac{M_{ctrl} - M_{conc}}{M_{ctrl}} \times 100\% \tag{1}$$

$$\text{Strength deterioration factor (SDF)} = \frac{F_{ctrl} - F_{conc}}{F_{ctrl}} \times 100\% \tag{2}$$

where M_{ctrl} = average mass of control specimen (0% $MgSO_4$); M_{conc} = average mass of specimen after curing in the $MgSO_4$; F_{ctrl} = average compressive strength of control specimen (0% $MgSO_4$); F_{conc} = average compressive strength of specimen after curing in $MgSO_4$ (1%, 3%, 5%).

3. Results and Discussion

3.1. Workability

Slump test was used as a measure of the workability of Coir Fibre Reinforced Concrete (CFRC) at an initial w/c ratio of 0.5. It was observed that at both levels of CF inclusion (0.5 and 1%), slump value was reduced to zero, making the CFRC barely workable. Therefore, the w/c ratio was increased to 0.55, which produced a fair, workable mix with slump values ranging from 5-20 mm. Various authors have attested to the fact that fibres reduce the slump of concrete significantly. The works of Abhishek et al. [31], Al-Kadi et al. [32] and Shreeshail et al. [33] revealed that the inclusion of CF in concrete at varying proportions decreased its workability drastically using various test methods (slump, slump flow, V-Funnel, compaction factor, vee bee test, flow table test). Furthermore, Ali et al. [34] reported that at 0.48 w/c ratio, prepared CFRC (with 1-3%, 5% CF) was not workable until an increment of the w/c ratio from 0.49 to 0.62. Despite low slumps recorded for this study, the CFRC was fairly workable. Hence, the use of slump cone and value for workability test for Fibre Reinforced Concrete (FRC) has been discouraged as a general discourse among researchers.

The low workability observed for the CFRC can be due to various reasons. CF is a water-absorbent material, absorbing water to the tune of 71.3-150% [35, 36]. Therefore, during mixing of the matrix, the fibres can absorb the mixing water and swell, thereby pushing away the concrete matrix [36]. This initially reduced workability and later improved it minimally when w/c ratio was increased [34]. The CF is more elongated than the aggregates; this will promote interlocking and friction in the matrix [37] thereby reducing workability. Furthermore, the specific surface area of CF is higher than that of the aggregates [38, 39], resulting in increased water demand [37], thereby making CF require more water to lubricate its surface. Sivaraja et al. [3] limited their CF to 1% to avoid the balling effect on concrete during mixing. Likewise, the study opined that optimum fraction of 1.5% is evident in literature for concrete without water reducing admixtures. Other studies that went above 1% CF inclusion either made use of superplasticizer [4, 18, 31, 32] or were silent on the workability requirements [35, 40-43]. Hence, CFRC at >1% may require the use of water reducers.

3.2. Density

This study revealed that the inclusion of CF (0.5 and 1%) in concrete has a negligible effect on its density. The density of plain concrete, 0.5 and 1% CFRC was averagely 25 g/cm^3 at all curing ages. This is expected as the density of CF (1.18 g/cm^3 [27]) is relatively low to that of normal concrete. Hence, the level of incorporation of CF in concrete for this study is relatively low to affect its density. This result follows the study of Hassan et al. [36] where CF reduced concrete density significantly only at 5 and 7% and not at 1 and 3%. The result of Ali et al. [34] also reported a density reduction of 0.4% at 1% CF, and 4% at 5% CF in concrete.

3.3. Compressive strength result

Figures 3 and 4 show the results obtained for the compressive strength of the specimens at 7, 14, 28 and 56 days. Generally, as the curing age increases, the compressive strength also increases for both batch mixes. The inclusion of CF slightly improved the compressive strength of concrete with 0.5% CF having higher compressive strength than 1% CF. For Batch A mixes, 0.5% CF improved the compressive strength of the plain concrete by 21.8, 7.6 and 14.3% at 7, 14 and 28 days, respectively. At 1% CF content for Batch A mixes, compressive strength only marginally increased at 7 and 56 days. For Batch B mixes, 1% CF has no significant improvement on the compressive strength of the plain concrete. Similar to this study, Santra and Chowdhury [12] reported an increase in compressive strength at 0.2 and 0.4% CF. This implies that potential for improvement in compressive strength may reach its limit at 0.5% CF; from some literature, slightly increasing CF above 0.5% may not drastically reduce the compressive strength (around 1%)

but there’s often a downward trend as CF content increases further. Such studies have at least CF ≥ 1% and optimum CF that yields lower strength than the control [4, 36, 41, 44].

Since there are only slight or no improvement from the variation of CF content for each batch, other variables could have been responsible for the slight differences (such as manual mixing and compaction) and not necessarily a direct relationship with the CF.

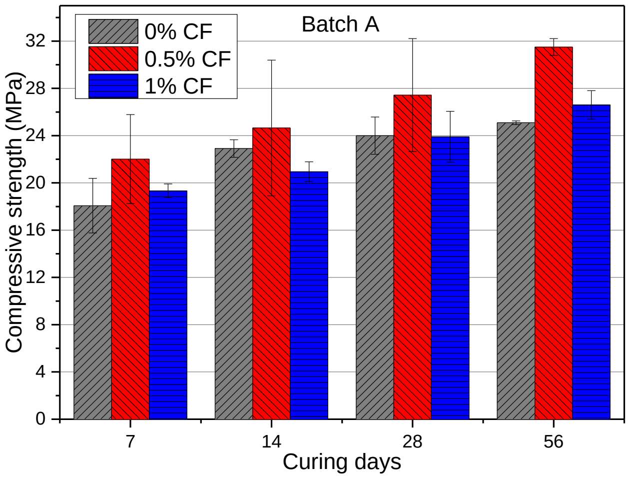

Fig. 3. Variation of compressive strength with CF content.

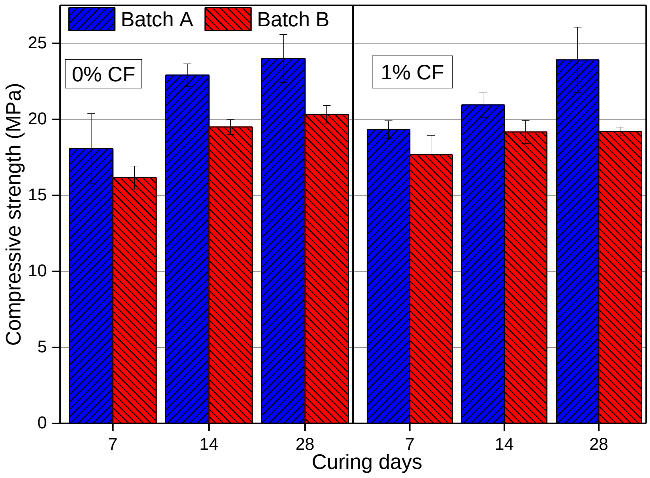

Fig. 4. Variation of compressive strength with mix proportion.

This implies CF slightly improves the compressive strength of concrete. Likewise, the mix ratio influences the effectiveness of CF in improving the compressive strength of concrete. The richer mix (Batch A) will have more cement to hydrate and bind the matrix together; this may improve the CF bond to the matrix. Ali et al. [5] opined that increased CF bond strength improves CFRC resistance to compressive stress.

Figure 4 shows the effect of the mix proportion on the compressive strength at various ages of curing. At all the curing ages and CF content (0 and 1%), Batch B specimens had slightly less strength than those of Batch A. However, the inclusion of CF in Batch B makes its 7-day strength equal to that of the plain concrete in Batch A. Results of this study are in line with that of previous studies, which indicate that optimum inclusion of CF in concrete range from 0.6 to 1%. Ramli et al. [4] reported an optimum increase of 3.1% in compressive strength for 0.6% CFRC. Likewise, Abhishek et al. [31] reported an optimum of 0.8% CF inclusion in concrete. Ali et al. [45] reported an increase of 9% for 1% CFRC and a decrease of 6 and 10% for 2 and 3% CFRC, respectively. However, the CF used by Ali [11] was pre-treated by soaking in boiling water for 2 hours. This could have been responsible for the improved strength. On the other hand, Hassan et al. [36] reported a decrease of 17, 40, 50, and 73% in compressive strength due to the inclusion of 1, 3, 5 and 7% CF (volume percentage), respectively, in concrete. Sai et al. [41] reported a decrease of 4% at 2% CF without detailing the properties of the CF while Ogunbode et al. [44] had the closest compressive strength to the control at 0.5% CF at a reduction of 4% and 1% yielded a reduction of 11%.

3.4. Splitting tensile strength result

Figure 5 shows the splitting tensile strength results of the 0, 0.5 and 1% CFRC. Generally, the same pattern observed for the compressive strength is also observed. As the curing age increases, the tensile strength increases; inclusion of coir fibre marginally improved the early strength (7 days) of the concrete for both mix proportions. At 14 and 28 days, the coir fibre had little or no effect on the splitting tensile strength. At 7 days curing, Batch A had an increment of 7.4 and 13.8% for Batch B. At 14 days, Batches A and B had a decrease of 1.2 and 1.5%, respectively; while at 28 days, Batch A improved in strength by 2.6% and Batch B decreased in strength by 11.5%. However, it should be noted that Batch A had inclusion of 0.5% CF and Batch B had 1% CF inclusion.

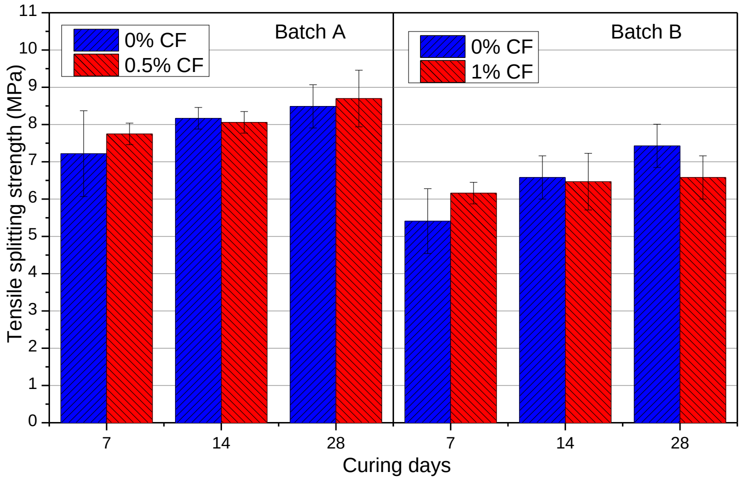

Fig. 5. Variation of tensile splitting strength with CF content.

Previous studies on the tensile strength of CFRC gave varied results. The study by Ali [11] revealed that the inclusion of 1, 2 and 3% CF (5 cm fibre length) in concrete improved the tensile strength by 11, 13 and 8%, respectively, while 5% CF reduced the tensile strength by 2%. The work of Shreeshail et al. [33] revealed that 1, 2 and 3% CF in concrete improved the tensile strength by 6, 29 and 23%, respectively, while Yalley and Kwan [18] reported that 0.25% CF did not improve the splitting tensile strength of concrete but 0.5 and 0.8% improved the strength by 15 and 3.2%, respectively. Furthermore, Ogunbode et al. [44] reported an increase of 1.19, 6.87 and 3.28% for 0.5, 1, 1.5% CF content.

3.5. Durability test result

Durability test of the CFRC was investigated by total immersion in 0 (control), 1, 3 and 5% $MgSO_4$ after curing in water for an initial 28 days. Compressive strength and mass were recorded after 28 and 56-day immersion. Thereafter, compressive strength loss and mass loss were calculated as Strength Deterioration Factor (SDF) and Mass Deterioration Factor (MDF).

3.5.1. Strength deterioration factor

Figure 6 shows the effect of coir fibre on the resistance of concrete to $MgSO_4$ attack. Firstly, it is interesting to observe that at 28 days of curing in 0% $MgSO_4$ (making a total of 56 days water curing), the compressive strength had been improved by 47 and 24% at 0.5 and 1% CF contents, respectively, above specimens with 0% CF content. The result at 28-day immersion in 1% $MgSO_4$ reveals that the compressive strength of 0 and 1% CFRC in 1% $MgSO_4$ is higher than that in water (0% $MgSO_4$) by 10 and 2.95%, respectively. This reveals that at 28 days in 1% $MgSO_4$, the concrete specimens (0 and 1% CFRC) were still gaining strength. This would mean that the formation of disruptive gypsum and ettringite is still filling available voids [46].

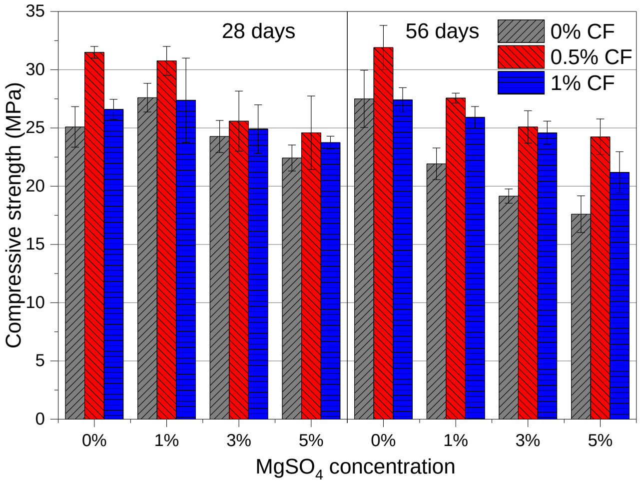

Fig. 6. Variation of coir fibre with compressive strength at various percentages of $MgSO_4$ concentration.

From Fig. 7, at 0.5 and 1% content of CF, an SDF of ±2% was recorded on the 28-day in 1% $MgSO_4$. The strength loss/gain is therefore negligible. At 3% $MgSO_4$, 0.5% and 1% CFRC underwent more deterioration (SDF = 18.8 and 6.3%, respectively) than the plain concrete (SDF = 3.3%). The higher SDF obtained for 0.5% CF could have resulted because the available voids are partly filled up by CF while the disruptive ettringite and gypsum have overfilled the remaining voids and causing internal cracks that weaken the strength. However, unlike the 1% CFRC, the 0.5% CF inclusion is not enough to adequately resist (by bridging internal cracks) the expansive nature of ettringite and gypsum. At 5% $MgSO_4$, 1% CF has same strength deterioration as plain concrete (SDF = 10.7%), with 0.5% CFRC deteriorating more in strength than the plain concrete (0% CF). At 56 days of immersion of specimens in $MgSO_4$, the deleterious effect of $MgSO_4$ attack has begun to set in (all immersed specimens had positive SDF). This sulphate resistance pattern can also be explained by the same reason given for the 28-day immersion. Generally, the higher the $MgSO_4$ concentration, the higher the strength deterioration as expected. From the foregoing, incorporation of 1% CF improved the concrete resistance to $MgSO_4$ attack at all concentrations (1, 3 & 5%) more than 0% and 0.5% CF.

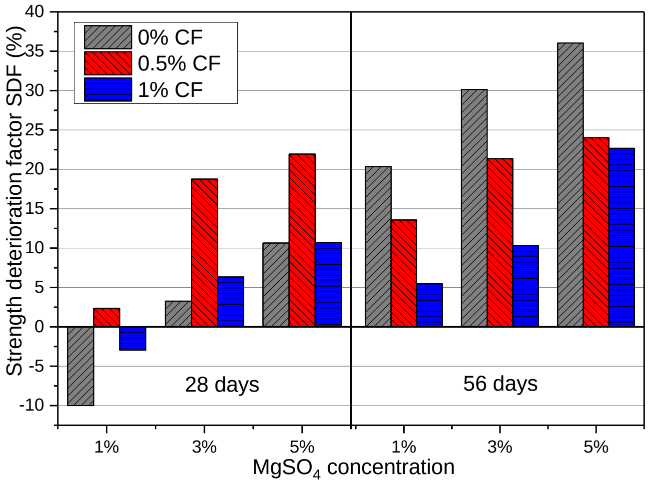

Fig. 7. Variation of strength deterioration factor with CF content in $MgSO_4$ solution.

As found in this study, previous studies on CFRC show that the incorporation of CF improved the durability properties of concrete. According to Ramli et al. [4], incorporation of 0.6 and 1.2% CF in concrete improved its ultimate (546 days) durability in terms of strength. Nithin and Sheeja [40] reported 1% CF in concrete as the optimum dosage against sulphuric acid and sodium sulphate attack. In the study of Sivaraja et al. [3], 1.5% incorporation of CF in concrete effectively improved the resistance to 5% sulphuric acid and freeze-thaw cycles.

3.5.2. Mass deterioration factor

Figure 8 shows the mass deterioration factor (mass loss) at 28 and 56 days of immersion in $MgSO_4$ after 28 days of initial curing in water. The 5% $MgSO_4$ had the most significant effect at both 28 and 56-day immersion periods. At 0.5% CF content, the higher the concentration of $MgSO_4$, the more the mass deterioration with 56-day immersion having slightly less deterioration than 28 days. At 1% CF content, 28-day immersion specimens increased in mass in 1% $MgSO_4$ solution, remain unchanged in 3% $MgSO_4$, and reduced in 5% $MgSO_4$. However, when immersed for 56 days, 1 and 3% $MgSO_4$ increased its mass while 5% $MgSO_4$ increased its mass proportionately. From the results, it is clear that 0.5% of CFRC underwent the worst mass deterioration at both immersion periods, followed by the plain concrete (0% CFRC). Furthermore, Fig. 8 reveals that the variation in mass due to deterioration is not much as that of strength. This could be because the disruptive gypsum and ettringite in the specimens are not leaching away easily (especially with the CF bridging the mass together), thereby contributing to the mass of the specimen. This explains the lower MDF at 56 days as compared to that of 28 days for the CFRC.

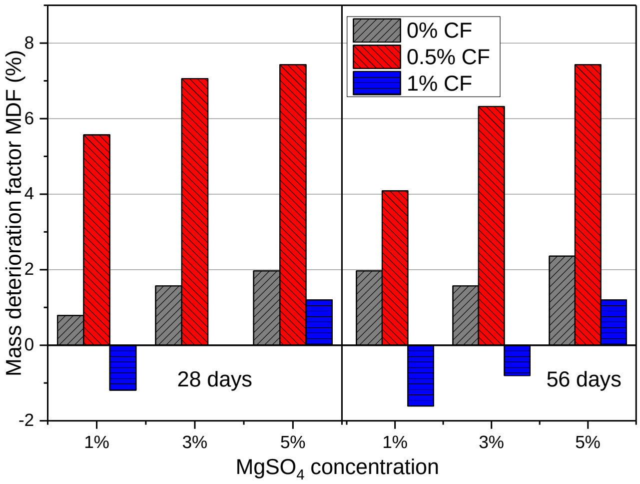

Fig. 8. Variation of mass deterioration factor with CF content in $MgSO_4$ solution.

From the foregoing, there exists no definite pattern of the effect of $MgSO_4$ concentrations and immersion days on the mass deterioration factor of CFRC. This agrees with the submission of Olusola and Babafemi [47] on the mass deterioration of *kernelrazzo*. On the other hand, 0.5% CF inclusion in concrete worsens the mass deterioration than that of the control (0% CFRC) while 1% CFRC outperform the control. This is in line with what was observed for the strength deterioration factor.

4. Conclusions

Based on the findings of this investigation on the mechanical and durability properties of coir fibre reinforced concrete, the following conclusions can be made.

- The inclusion of 0.5 and 1% CF in concrete had no effect on its density; that is, the density of plain concrete, 0.5% CFRC and 1% CFRC were relatively the same.
- Introduction of CF in concrete slightly improved its compressive strength (7.6 - 21.8%). The tensile strength was only improved slightly at an early age (7.4

- 13.8%). 0.5% CF content improved the strength of concrete more than 1% CF content.

- Richer mix proportion improves the effectiveness of CF in concrete, implying that its bond strength with concrete matrix was improved.
- CF incorporation in concrete improved its resistance to sulphate attack (in terms of mass loss and compressive strength loss); 1% CF inclusion improved concrete's resistance (SDF = 5.47, 10.32, 22.68%) more than 0.5% CF inclusion (SDF = 13.56, 21.36, 22.68%).
- Unlike the compressive strength loss, there was no definite pattern as to the effects of $MgSO_4$ concentration and immersion period on the mass loss of CFRC.

As a recommendation for future study, other factors that influence the properties of CFRC can be investigated. These include CF pre-treatment, aspect ratio, w/c ratio, tensile pull-out test, flexural strength.

Nomenclatures

C_c	Coefficient of curvature
C_u	Coefficient of uniformity
F_{conc}	Average compressive strength of specimen after curing in the $MgSO_4$
F_{ctrl}	Average compressive strength of control specimen (0% $MgSO_4$)
M_{conc}	Average mass of specimen after curing in $MgSO_4$
M_{ctrl}	Average mass of control specimen (0% $MgSO_4$)

Abbreviations

CF	Coir Fibre
CFRC	Coir Fibre Reinforced Concrete
FRC	Fibre Reinforced Concrete
MDF	Mass Deterioration Factor
$MgSO_4$	Magnesium Sulphate
OPC	Ordinary Portland Cement
SDF	Strength Deterioration Factor

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