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ORIGINAL PAPER

Mechanical characterisation of sustainable fibre-reinforced lightweight concrete incorporating waste coconut shell as coarse aggregate and sisal fibre

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Abstract

The construction industry is largely dependent on concrete as a construction material. The aggregate occupies a major volume of concrete. However, the continuous extraction of granite rock for coarse aggregate leads to the increase in demand of natural resources of future generations. In this study, coconut shell, an agricultural waste, is used to replace conventional aggregate in concrete for producing coconut shell lightweight concrete. To enhance the weak mechanical characteristics of lightweight concrete, various contents of sisal fibre at 1%, 2%, 3% and 4% have been added on the basis of the binder's weight. Mechanical properties, such as compressive strength, split tensile strength, flexural strength, elastic modulus and impact resistance, were examined. Results showed that the compressive strength increased by up to 6% when 3% fibre was added. An improvement in split tensile strength of 14%, flexural strength of 11% and modulus of elasticity of 6% was observed when a maximum of 3% fibre was added. Impact resistance was also excellent after the addition of sisal fibre. Thus, coconut shell concrete with sisal fibre is considered as a suitable and eco-friendly construction material alternative for the construction industry.

Keywords Agricultural waste · Fibre-reinforced concrete · Fly ash · Lightweight concrete · Natural fibre · Sustainability

Introduction

Concrete is the second most consumed element next to water in the world and is a commonly used construction material (Meyer 2009). The production of concrete exceeds 10 billion tons annually. The use of concrete has accelerated because of the advancements in infrastructure worldwide. However, the extensive use of the material has also caused some drawbacks, such as the continuous large extraction of aggregate from natural resources, and led to the deficiency of resources and ecological imbalance. To date, the construction industry is seeking for clean and green concrete solutions to achieve a sustainable and eco-friendly construction. One of the approaches adopted by researchers is by replacing coarse aggregate with alternative sources to make concrete more economical and lead towards sustainable development (Gunasekaran et al. 2011). Granite aggregate sources are exhausting rapidly because of the shortage in natural resources that is caused by the rapid growth in the construction sector.

Coconut shell (CS) is a common waste generated from the agricultural industry of tropical countries, such as India (Prakash 2017). CS is seldom recycled in the construction sector and is often disposed as waste. After drying under sun, CS consists of varying percentages of cellulose, lignin and wax. The use of CS as coarse aggregate in the production of lightweight concrete (LWC) is a new approach in concrete production (Gunasekaran et al. 2017). Coconut crop can be found nearly all over the world, excluding Europe and Australia, and is cultivated in more than 93 countries. The average annual production of coconut is approximately 67 billion nuts or 12 million metric tons

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of copra equivalents. At least 50% of the world's coconut production is processed into copra. The three largest producers of coconut include Indonesia, Philippines and India, which account for 75% of the world's CS production (Prakash et al. 2020a, b, c). In India, CS occupies nearly 60% of the total domestic waste and presents a significant disposal issue for the local environment. Once the coconut is scraped off the shell, CS is commonly discarded as waste. The discarded CS can be crushed into a required size and recycled as a coarse aggregate to produce LWC. CS concrete can be adopted in rural areas where coconut trees are cultivated in abundance. This type of concrete has the dual benefit of cost minimisation in construction materials and a waste clearance method.

The cement industry is a major contributor to global warming because of its high carbon dioxide (CO_2) footprint (Al-Amoudi et al. 2017; Al-Sodani et al. 2018; Raman et al. 2011). Cement industry alone contributes at least 5% of the anthropogenic emission out of the 25% of the total global CO_2 emission from the industrial sector. In addition, research has shown that 85% of the CO_2 emission contributed throughout the lifecycle of concrete structures comes directly from cement production (Habert and Roussel 2009; Lim et al. 2018). The usage of cement in concrete production can be reduced by introducing locally sourced by-products and alternative resources with low-carbon footprint as supplementary cementitious materials in concrete production. The present study focuses on the utilisation of an industrial waste, fly ash, which is generated as by-product from coal-fired power plants as a partial supplement for cement. The environmental load in the use and disposal of fly ash has posed challenges to the power generation industry. The incorporation of fly ash in concrete not only resolves its disposal challenges, but also reduces the emission of greenhouse gases due to the decreased usage of cement in concrete. Replacing a significant portion of cement with fly ash in concrete can reduce carbon emission into the atmosphere effectively.

LWC is 20–25% lighter than conventional concrete (Lo and Cui 2002), which makes the reduced handling and transportation costs of the material a desirable feature (Divyah et al 2020). Structural LWC offers good flexibility, lower dead weight, satisfactory seismic response and reduced foundation costs (Nagarajan et al 2020). The use of precast elements that are made of LWC provides reduced conveyance and erection costs. The main disadvantage of LWC is the need for increased cement usage to achieve the equivalent strength of conventional concrete. However, this drawback can be overcome by substituting a portion of cement with industrial waste with pozzolanic properties. Shafigh et al. (2013) found that the strength of oil palm shell (OPS) LWC improved after replacement of 10% cement with fly ash. Similarly, Prakash et al. (2019) also deduced that 10% fly ash replacement level in CS concrete significantly improved the strength of CS concrete.

On the other hand, the practice of incorporating fibres into building materials has been a practice since ancient times in many parts of the world. This effort was mainly motivated by the need to enhance the tensile capacity of the 'perceived' brittle characteristics of the materials. This technology was adopted in the derivation of fibre-reinforced concrete (FRC) in the twentieth century, which has found increased attention and application in the construction industry, mainly due to its improved strength and stiffness. The practice of using natural fibres as secondary reinforcement in concrete provides an environmental-friendly alternative to synthetic fibres (Rokbi et al. 2019). Natural fibres, such as sisal, kenaf, banana, flax, jute, curaua, hemp and coconut sheath, are considered potential alternatives for synthetic fibres (Mohanty et al. 2000; Kabir et al. 2012). Sisal fibres have high amounts of cellulose component, which account for the increased tensile strength, and they do not absorb water easily. Amongst several natural fibres, the sisal fibre is the most used material in the construction sector because of its cost-effectiveness, remarkable acoustic and thermal characteristics, satisfactory tensile strength, high toughness and abrasion resistance and abundance.

The present work was undertaken to study the influence of fly ash as cement replacement, and plant-based natural sisal fibre on the mechanical properties, i.e. compressive strength, split tensile strength, flexural strength, elastic modulus and impact resistance of LWC produced with CS aggregate. Although the use of natural fibres in LWC (Sadiqul Hasan et al. 2012) and CS aggregate in concrete (Jayaprithika and Sekar 2016) had been studied in the past, the combined use of CS aggregate and sisal fibres in concrete is yet to be explored. Henceforth, this study investigates the influence of sisal fibre incorporation at 1.0%, 2.0%, 3.0% and 4.0% (based on the weight of binder) on the properties of LWC produced with CS aggregate with a constant partial replacement of fly ash. This experimental work was performed at the Structural Engineering Laboratories of Alagappa Chettiar Government College of Engineering and Technology in Karaikudi, India.

Materials and methods

Materials

Ordinary Portland cement (Grade 53) conforming to IS:12269-1987 with a specific surface area of 3350 cm^2/g and specific gravity of 3.13 was used in this study. The initial and final setting times of the cement are 65 min and 140 min, respectively. Class F fly ash with a specific surface area and density of 7290 cm^2/g and 2130 kg/m^3, respectively, was utilised as supplementary cementitious material. River sand from Cauvery River conforming to Zone II was used as fine aggregate. Its specific gravity and fineness modulus were 2.36 and 2.91, respectively.

Meanwhile, the CS sample was collected from a local copra preparation yard, located in the Thanjavur District in Tamilnadu, India. The CS sample was subsequently hammered and crushed into smaller pieces and sieved. Crushed CS samples with a size range of 12.5–4.75 mm were used as coarse aggregate. The prepared CS aggregate was washed with clean water and then dried under the sun. Given the remarkable moisture holding capacity of CS aggregates, it must be soaked in water for 24 h. The soaked CS aggregates were then dried to remove the surface water before being used in concrete, to correspond to the saturated surface dry (SSD) condition of the aggregate. When the CS aggregate is in SSD condition, it will not further absorb water from concrete, so workability of the resulting concrete will not be affected. Figure 1a shows the accumulated CS waste of the copra preparation yard. This CS waste was collected and then crushed into aggregates (Fig. 1b). Table 1 lists the physical properties of CS aggregate. Bore well water available within the college premises was utilised for the concrete mixing purposes, while Conplast SP430 was used as the water-reducing admixture in the mixtures.

Sisal fibre belongs to the species Agava, and its botanical name is Agave sisalana. This plant can be found in southern part of India, especially in Tamilnadu, Kerala, Karnataka and Andhra Pradesh. The characteristics of the fibres depend on the properties of the individual constituents, the fibrillary structure and the lamellae matrix. The fibre is composed of numerous elongated fusiform fibre cells that taper towards the end. The fibre cells are linked together by means of middle lamellae, which consist of hemicelluloses, lignin and pectin (Sorieul et al. 2016; Maya et al. 2017). The fibre was used in the present study to enhance the structural quality, tensile and ductility capacity, and to achieve sustainability of the composite. The physical properties the sisal fibre indicated the absence of deterioration in a concrete medium. The leaves were firstly dried and then brushed and lastly baled for fibre extraction. Figure 2 shows the sisal fibre extracted from the leaves of sisal plant. The properties of sisal fibre are presented in Table 2.

Mix proportion and procedure

Mixtures were prepared on the basis of ACI 211.2, and the mixture performed according to the specified criterion was used in this investigation. Class F fly ash at 10% by weight was used to replace cement. The binder and fine aggregate contents were kept constant at 460 kg/m^3 and 750 kg/m^3, respectively. A total of 1.0%, 2.0%, 3.0% and 4.0% of sisal fibre were incorporated based on the weight of binder, and these mixtures were labelled as CSC1, CSC2, CSC3 and CSC4, respectively. A water-to-cement ratio of 0.33 was maintained for all mixtures. The high-range water-reducing agent, Conplast SP430, with a dosage of 1.2% by weight of binder was added to increase the workability of concrete. Table 3 presents the proportion of all the mixtures.

Table 1 Physical properties of CS aggregate

Properties	Values
Maximum and minimum size (mm)	12 and 4.75
Thickness (mm)	3–8
Water absorption (%)	25
Specific gravity	1.11
Fineness modulus	6.25
Bulk density (g/cm^3)	0.65
Void ratio	0.64
Crushing value (%)	2.59
Abrasion value (%)	2.0
Impact value (%)	7.9
Moisture content (%)	3.8


(a) (b)

Fig. 1 **a** Discarded CS waste from copra preparation yard. **b** Aggregates crushed from CS shell

Fig. 2 Raw sisal fibre extracted from the leaves of sisal plant

Table 2 Properties of sisal fibre

Properties	Values
Diameter	0.2–0.3 mm
Length	300 mm
Density	1.45 g/cc
Tensile strength	500–600 MPa
Modulus of elasticity	15–16 GPa
Water absorption	10%
Cellulose	72%
Hemicellulose	12%
Waxes	2%
Lignin	14%

To describe the sequence of mixing, the CS aggregate and river sand were mixed in the rotary drum mixer for about 3 min, followed by the addition of cement and fly ash for another 6 min. Then, water and superplasticiser were added into the drum and the mixing was done for another 8 min. Finally, sisal fibres were evenly distributed into the mixture and mixed. The mixture was then placed into moulds and compacted. The specimens were demoulded after 24 h and water cured till the date of testing.

Testing methods

The slump test was performed according to ASTM C143/C143M-12 prior to casting of the specimens. The specimens were demoulded 24 ± 2 h after casting. The compressive strength was determined according to IS 456:2000 using 100 mm cube specimens. Two cylinders (diameter: 150 mm, height: 300 mm) were used to determine the modulus of elasticity of the mixtures in accordance with ASTMC469-10. Meanwhile, three cylinders (diameter: 100 mm, height: 200 mm) and three prisms of size 100 mm × 100 mm × 500 mm were used to measure the 28-day split tensile strength and 28-day flexural strength, respectively. A 2000 kN capacity compression testing machine with a loading rate of 2.3 kN/s was used. Meanwhile, the impact test was performed on concrete discs (diameter: 152 mm, height: 63.5 mm) adopting the drop hammer impact technique.

Results and discussion

Slump of sisal fibre-reinforced CS concrete

The quality of the concrete construction depends not only on the quality of the constituent but also on the workability of the fresh concrete during transportation, placement and compaction. According to ASTM C125, the term 'workability' is a property that determines the effort required to work on a freshly mixed quantity of concrete with the least loss of homogeneity. The workability of LWC differs from that of normal-weight concrete. The large slump of LWC causes the lightweight aggregates to float away from the heavier cementitious matrix. This separation will then result in poor finishing and compaction. These reasons have prompted the ACI 213R-87 to restrict the slump of LWC to a maximum of only 100 mm for satisfactory finishing and compaction (Mehta and Monteiro 2006). Mehta and Monteiro (2006) suggested that a 50–75 slump was adequate for LWC to achieve good compaction and finishing. Hossain (2004) stated that a high

Table 3 Mix proportion of sisal fibre-reinforced CS concrete

Mixture ID	Cement (kg/m^3)	Fly ash (kg/m^3)	Fine aggregate (kg/m^3)	CS aggregate (kg/m^3)	*w/b*	Superplasticiser %	Sisal fibre %
CSC	460	50	750	332	0.33	1.2	0
CSC1	460	50	750	332	0.33	1.2	1.0
CSC2	460	50	750	332	0.33	1.2	2.0
CSC3	460	50	750	332	0.33	1.2	3.0
CSC4	460	50	750	332	0.33	1.2	4.0

slump was unnecessary for good finishing and compaction of LWC because the work done of lightweight aggregate by gravity was remarkably lower.

On the other hand, the workability of FRC is generally lower than that of plain concrete. The fibres in the concrete mixture alter the concrete matrix by forming a network of fibres. Consequently, this network limits the flowability and hence reduces the workability of concrete. Atis (2003) observed a reduction in the workability of mortar and cement paste as the quantity and length of jute fibres increased. Savastano et al. (2000) observed the reduced workability of cement composites reinforced with eucalyptus pulp and coir or eucalyptus pulp combined with sisal fibres. The decrease in the workability was due to the absorption of moisture with respect to the hydrophilic nature of the fibres. The flowability and workability of LWC can be improved by adding a superplasticiser (Lu et al. 2008; Okamura and Ouchi 2003).

In the present study, although CS aggregate tends to have high water absorption, it will not absorb water during the mixing process because it was used under saturated surface dry conditions. Hence, the workability of the mixture may be unaffected. In this study, the water and superplasticiser contents were kept constant for all the mixtures. The sisal FRC recorded a lower slump value than the control mixture. Figure 3 shows that the increase in sisal fibre decreased the slump value of the CS concrete mixture. The addition of 1.0%, 2.0%, 3.0% and 4.0% fibre decreased the slump by 7%, 21%, 28% and 50%, respectively. When the fibres were spread into the concrete mixture, the viscosity of the concrete mixture increased because of the formation of the binder matrix–fibre network structure; consequently, the workability and flowability of the mixture decreased (Chen and Liu 2005). FRC consumes additional cement paste when an increased amount of fibre is added for the coating around the fibre. This additional consumption in turn reduces the workability of concrete. Thus, the mixture with 1.0% sisal fibre obtained the lowest slump but could still be consolidated adequately. Figure 4 illustrates the linear empirical equations that relate sisal fibre content to slump of mixtures reinforced with sisal fibre. It can be seen that a very high coefficient of determination (0.9633) was achieved.

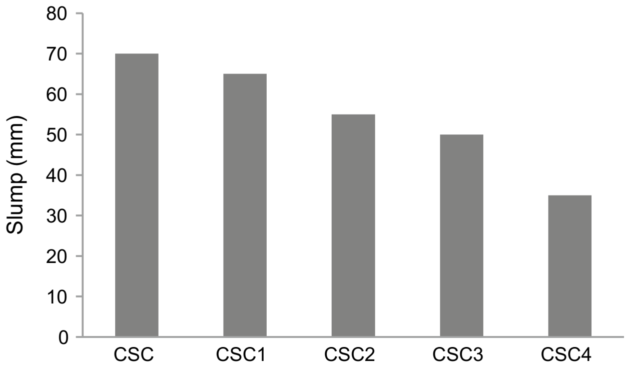

Fig. 3 Influence of sisal fibre content on slump of CS concrete

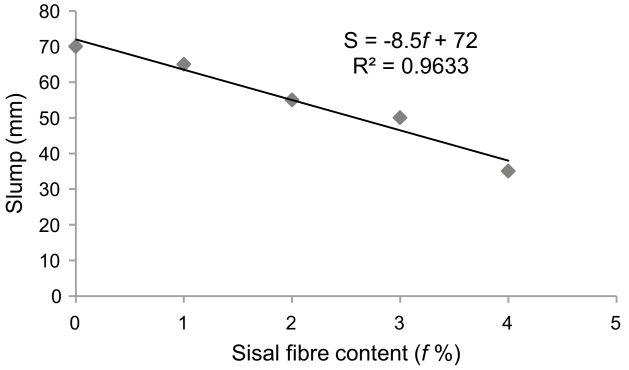

Fig. 4 Correlation between sisal fibre content and slump of CS concrete

Density of sisal fibre-reinforced CS concrete

The density of structural LWC lies in the range of 1600–2000 kg/m^3 (Newman and Choo 2003). Notably, the density of concrete slightly decreases when the content of fibre increases. This density reduction is caused by the low value of specific gravity of sisal fibre in the mixture. All the mixtures recorded a density below 2000 kg/m^3, which satisfies the density requirement of LWC. Figure 5 shows the density of sisal fibre-reinforced CS concrete. The maximum density reduction of 3.1% was reported for the addition of 4.0% fibre. The decreased density reduces the overall weight of the structure. Hence, the foundation cost decreases. Figure 6 illustrates the linear empirical equations that relate sisal fibre content to density of mixtures reinforced with sisal fibre. It can be observed that a very high coefficient of determination (0.9851) was obtained.

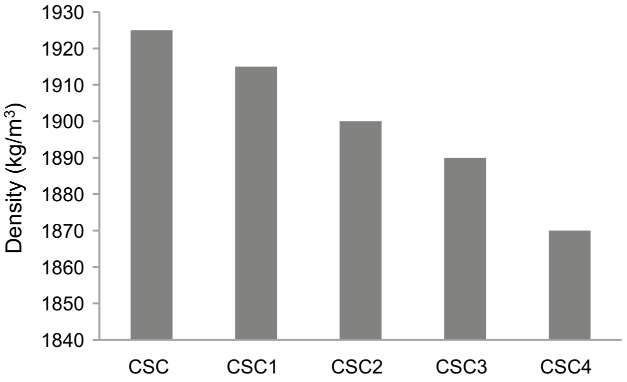

Fig. 5 Influence of sisal fibre content on density of CS concrete

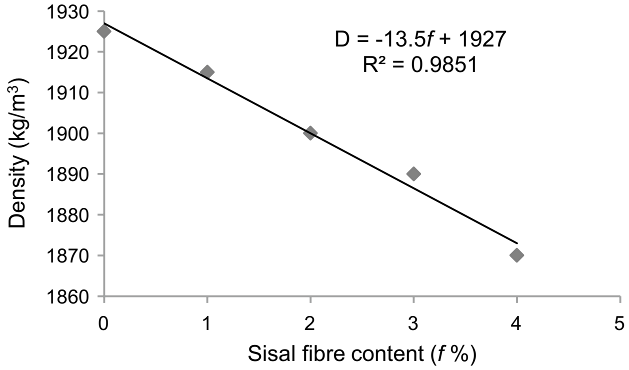

Fig. 6 Correlation between sisal fibre content and density of CS concrete

Compressive Strength of sisal fibre-reinforced CS concrete

The compressive strength values at 28, 56 and 90 days of CS concrete mixtures for different contents of sisal fibre are presented in Table 4. In this study, the addition of sisal fibre normally improved strength. Amongst the various percentages of added sisal fibre, the mixture containing 3.0% sisal fibre (CSC3) recorded the highest compressive strength at 28, 56 and 90 days. The compressive strength increased by approximately 6% at 28 days, as compared with the control CS concrete mixture. The significant increase in compressive strength at 56 and 90 days was caused by the enhanced pozzolanic activity of fly ash that occurred at later ages. Prakash et al. (2019) achieved a compressive strength of 35.6 MPa in CS concrete. Further, Prakash et al. (2020b) enhanced the compressive strength of CS concrete up to 36.8 MPa by incorporating polypropylene fibre. In this study, the compressive strength of 37.6 MPa was achieved for sisal fibre addition. Ali et al. (2012) obtained a maximum of 24% increase in compressive strength when coir fibre was incorporated into concrete. Mukhopadhyay and Bhattacharjee (2014) found that the addition of banana fibre improved the compressive strength of a concrete block. When compressive load increases, it will initiate crack development in the concrete structure. When the crack approaches the location of fibres, the debonding of the fibre–matrix interfaces will begin because of the stress that developed perpendicular to the crack path. When a significant amount of tensile stress was induced in the concrete, microcracks subsequently develop (Yew et al. 2015). This phenomenon revealed that the addition of sisal fibres enhanced the fibre–matrix interface of concrete and thus improved the compressive strength of CS concrete.

Table 4 Compressive strength of sisal fibre-reinforced CS concrete

Mixture ID	Compressive strength (MPa)		
	28 Days	56 Days	90 Days
CSC	35.6	41.2	44.5
CSC1	36.2	41.88	45.25
CSC2	36.9	42.69	46.13
CSC3	37.6	43.50	47.00
CSC4	34.6	40.03	43.25

Split tensile strength of sisal fibre-reinforced CS concrete

Tensile strength is an important property of concrete given that concrete members are often susceptible to cracking because of tensile loading, including its deadweight. The tensile strength of concrete is determined by conducting an extremely difficult task of splitting the tensile and flexural strength tests as uniaxial tension tests. In general, LWC possesses weak tensile strength. Therefore, the addition of fibre is a promising technique for overcoming the weak strength properties of CS concrete, especially the split tensile strength, without exceeding the density upper limit of LWC. A remarkable improvement in split tensile strength was achieved in steel fibre-reinforced CS concrete (Prakash et al. 2020a). The addition of polypropylene fibre increased the split tensile strength of CS concrete by 22% (Prakash et al. 2020b).

Table 5 lists the split tensile strength of sisal fibre-reinforced CS concrete. The addition of fibre generally improved the strength of CS concrete. The maximum improvement in split tensile strength of 14% at 28 days was obtained in the CSC3 mixture at 3.42 MPa, which is approximately 9.8% of the compressive strength of the corresponding mixture. Mandal et al. (2018) determined that the addition of coir fibre in CS concrete significantly improved its split tensile strength. Ali et al. (2012) obtained a 21% increase in the split tensile strength of concrete by incorporating coir fibre. Zhou et al. (2013) achieved higher split tensile strength in the cementitious composites of jute FRC than that of a plain concrete matrix.

In accordance with ASTM C330, the minimum requirement of split tensile strength of LWC for structural

Table 5 Split tensile strength of sisal fibre-reinforced CS concrete

Mixture ID	Split tensile strength (MPa)
CSC	3.01
CSC1	3.15
CSC2	3.26
CSC3	3.42
CSC4	2.98

application is 2.0 MPa. Therefore, all the mixtures in this experiment could be used as structural LWC.

Yap et al. (2013) derived Eq. 1 to determine the split tensile strength of polypropylene (PP) fibre-reinforced OPS concrete in terms of compressive strength:

$$f_t = 0.52\sqrt{f_c} \tag{1}$$

where f_t is the split tensile strength and f_c is the compressive strength

Yew et al. (2015) derived Eq. 2 to determine the split tensile strength OPS FRC in terms of compressive strength:

$$f_t = 0.55\sqrt{f_c} \tag{2}$$

In this study, regression analysis was employed and the empirical relations were developed between split tensile strength and compressive strength (Fig. 7). Considering the regression analysis, split tensile strength can be correlated with compressive strength using Eq. (3):

$$f_t = 0.5317\sqrt{f_c} \tag{3}$$

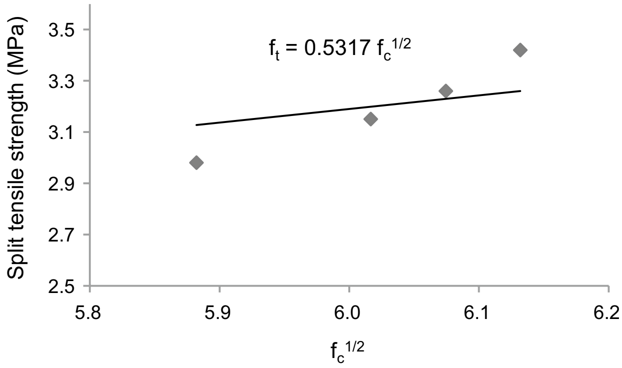

Fig. 7 Correlation between compressive strength and split tensile strength of sisal fibre-reinforced CS concrete

Figure 8 illustrates the comparison of the experimental and theoretical results of split tensile strength. It can be seen that the experimental results obtained are very close to the theoretical results predicted using Eq. 3.

Modulus of elasticity of sisal fibre-reinforced CS concrete

Modulus of elasticity is a key mechanical property of concrete that reflects the ability of concrete to deform elastically. Generally, LWC possesses a lower elastic modulus than normal-weight concrete of similar strength (Neville 2012). In general, the modulus of elasticity of concrete is affected by the stiffness of coarse aggregates (Gao et al. 1997; Campione et al. 2001). Lightweight aggregates have more pores and lower stiffness than those of conventional aggregates. Domagała (2011) reported that LWC possessed only approximately 45% of the elastic modulus value of conventional concrete with similar strength. Alengaram et al. (2008) found that OPS LWC produced high deflection and hence low modulus of elasticity because of the low stiffness of OPS aggregates. When CS concrete is subjected to compression loading, it produces high deflection; hence, lower modulus of elasticity is produced because of the lower stiffness of CS aggregates. A 17% increase in the modulus of elasticity was observed in CS concrete after the addition of steel fibre (Prakash et al. 2020a). The addition of polypropylene fibre in CS concrete improved its modulus of elasticity by 8% (Prakash et al. 2020b).

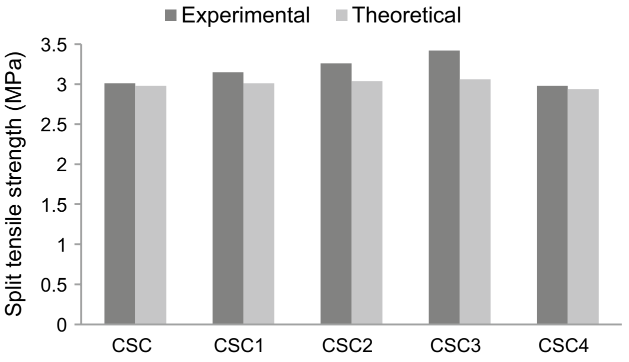

Fig. 8 Experimental and theoretical split tensile strength of sisal fibre-reinforced CS concrete

Table 6 presents the modulus of elasticity of CS concrete with various sisal fibre contents. A slight improvement in the elastic modulus was observed after the addition of sisal fibre in the CSC mixtures. The value of modulus of elasticity exhibited an increasing trend after adding up to 3.0% fibre but decreased after adding 4.0% fibre. The CSC3 mixture recorded the highest modulus of elasticity at approximately 6%, which is higher than that of the nonfibrous CS concrete. The static modulus of elasticity of other LWACs made of pumice (Hossain 2004), ignimbrite (Aydin et al. 2010) and expanded polystyrene (Sabaa and Ravindrarajah 1997)

Table 6 Modulus of elasticity of sisal fibre-reinforced CS concrete

Mixture ID	Modulus of elasticity (GPa)
CSC	15.17
CSC1	15.24
CSC2	15.37
CSC3	16.02
CSC4	14.38

was found within the range of 7.69–11.4 GPa. However, CS LWC produced a higher modulus of elasticity value than the other types of LWCs.

ACI 318 suggests the use of Eq. 4 for the prediction of the modulus of elasticity in terms of density and compressive strength of concrete:

$$E_c = 0.043w^{1.5}f_c^{0.5} \tag{4}$$

where E_c is the modulus of elasticity; w is the density of concrete, which ranges from 1400–2500 kg/m^3; and f_c is the compressive strength of concrete.

The Concrete Structural Design Standard Specification suggests the use of the following equation for relating the modulus of elasticity with the density and compressive strength of concrete:

$$E_c = 0.77w^{1.5}f_{cu}^{\frac{1}{3}} \tag{5}$$

where $f_{cu} = f_c + 8$ and f_c is the concrete compressive strength.

In this study, modulus of elasticity was correlated with compressive strength (Fig. 9). Considering the regression analysis, modulus of elasticity can be correlated with compressive strength using Eq. (6).

$$E_c = 0.0307w^{1.5}f_c^{0.5} \tag{6}$$

Figure 10 shows the comparison between the experimental and theoretical results of the modulus of elasticity. It can be seen that the experimental results obtained are very close to the theoretical results predicted using Eq. 6.

Flexural strength of sisal fibre-reinforced CS concrete

The flexural strength of CS concrete is presented in Table 7. For the control mixture, flexural strength was 5.17 MPa, which was approximately 14.5% of its compressive strength. In this study, the addition of sisal fibres in CS LWC had a beneficial effect on the flexural strength of concrete. Okafor (1988) showed that the rupture modulus of OPS concrete varied within the range of 4.3–6.2 MPa and reached a maximum compressive strength of 27%. Okpala (1990) obtained the flexural strength of OPS concrete within the range of 2.13–2.80 MPa, which is nearly 14% of its compressive strength. Teo et al. (2007) suggested that the flexural strength of OPS concrete varied at approximately 8 to 13% of its compressive strength. In this study, the addition of sisal fibres in CS concrete improved its flexural strength by 22%. The supplement of sisal fibre at 1.0%, 2.0% and 3.0% in CS concrete increased its flexural strength to approximately 2%, 8% and 11%, respectively. However, the addition of 4.0% fibre slightly decreased the flexural strength of CS concrete.

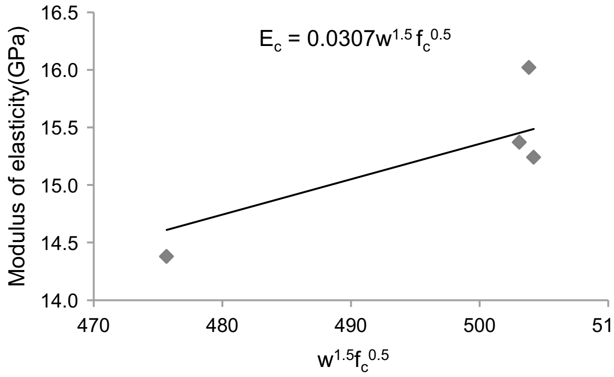

Fig. 9 Correlation of density and compressive strength with modulus of elasticity of sisal fibre-reinforced CS concrete

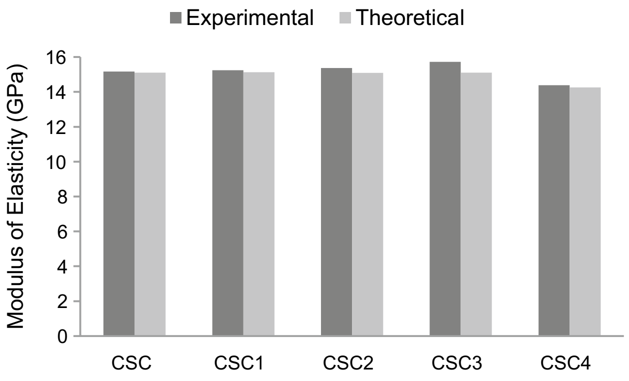

Fig. 10 Experimental and theoretical modulus of elasticity of sisal fibre-reinforced CS concrete

Mahmud et al. (2009) derived Eq. 7 for predicting flexural strength in terms of the compressive strength in the OPS concrete:

$$f_r = 0.30f_c^{2/3} \tag{7}$$

where f_r is the flexural strength.

Table 7 Flexural strength of sisal fibre-reinforced CS concrete

Mixture ID	Flexural strength (MPa)
CSC	5.17
CSC1	5.29
CSC2	5.59
CSC3	5.76
CSC4	5.07

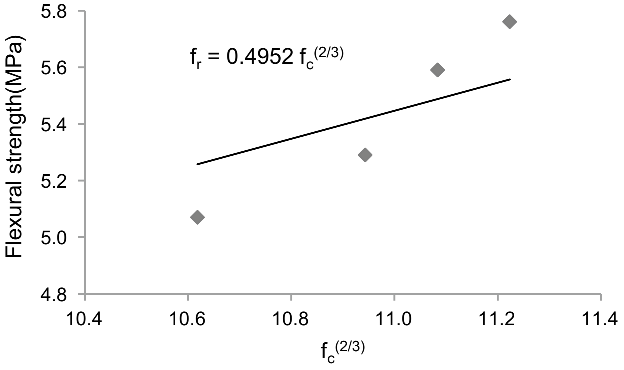

Fig. 11 Correlation between compressive strength and flexural strength of sisal fibre-reinforced CS concrete

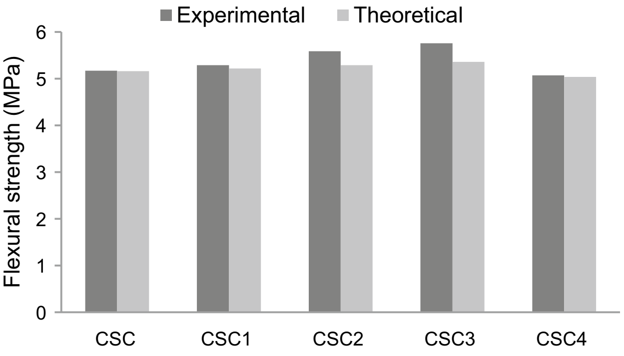

Fig. 12 Experimental and theoretical flexural strength of sisal fibre-reinforced CS concrete

Yew et al. (2015) suggested the use of Eq. 8 for predicting flexural strength in terms of the compressive strength in synthetic fibre-reinforced OPS concrete:

$$f_r = 0.385 f_c^{2/3} \tag{8}$$

Prakash et al. (2020b) demonstrated the flexural strength by using Eq. 9 in polypropylene fibre-reinforced CS LWC:

$$f_r = 0.526 f_c^{2/3} \tag{9}$$

In this study, based on the experimental data collected, flexural strength was correlated with compressive strength. Figure 11 depicts the regression analysis between flexural strength and compressive strength. Considering the analysis, flexural can be correlated with compressive strength using Eq. (10). Figure 12 shows the comparison between the experimental and theoretical results of the flexural strength:

$$f_r = 0.4952 f_c^{2/3} \tag{10}$$

Impact strength of sisal fibre-reinforced CS concrete

In general, the addition of synthetic fibres in concrete improves its ductility, impact resistance and toughness (Yap et al. 2013; Yew et al. 2015). Cementitious composites with plant-based fibre also obtained similar results. Ramakrishna and Sundararajan (2005) reported that the impact resistance properties of a cement composite slab with plant-based natural fibres were 3–18 times greater than those of the control concrete slab. Munawar et al. (2007) reported that the strain capacity of cement composites with coconut fibre was nearly 4–6 times higher than those of other plant-based fibre-reinforced composites.

Table 8 presents the results of the impact tests obtained in the present study. The results showed that the number of blows for the first crack and ultimate failure increased with the fibre content. Generally, concrete demonstrates brittle failure and offers minimal resistance after the formation of the first crack. However, the addition of fibre in concrete increases the number of blows required for ultimate failure. This improvement in postcrack resistance depends on the fibre content and increases with fibre content. The number of blows for ultimate crack in an unreinforced specimen was 37. However, this value increased with fibre content, and the maximum value of 83 was obtained after the addition of 4.0% fibre. The postcrack resistance of fibre-reinforced composites also increased with fibre content. The number of blows after the first crack was 23 and 44 for the specimen with unreinforced specimens and those with 4.0% fibre content, respectively. Sudarisman et al. (2015) found that the increasing content of bamboo fibre improved the impact resistance of concrete. Zhou et al. (2013) improved the impact properties of a cement

Table 8 Impact resistance of sisal fibre-reinforced CS concrete

Mixture ID	Number of blows for initial crack (N1)	Number of blows for ultimate crack (N2)	Impact energy (N2–N1) * mv^2/2 (N m)
CSC	14	37	467.94
CSC1	26	57	630.70
CSC2	32	66	691.73
CSC3	35	74	793.46
CSC4	39	83	895.18

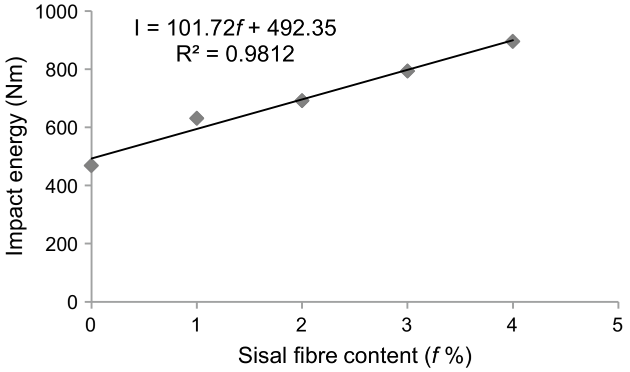

Fig. 13 Correlation between sisal fibre content and impact energy of sisal fibre-reinforced CS concrete

mortar panel reinforced with jute fibre. The addition of kenaf fibre enhanced the impact strength behaviour of high-density polyethylene composite (Aji et al. 2012). Given that fibres are spanned crosswise the cracks, the impact energy can be absorbed, and the crack advancement within the concrete is prevented. In this study, the impact energy of fibre-reinforced specimens increased by 35%, 48%, 70% and 91% after adding 1.0%, 2.0%, 3.0% and 4.0% fibre, respectively.

Figure 13 depicts the linear empirical equations that relate sisal fibre content to impact energy of mixtures reinforced with sisal fibre. It can be observed that a very high coefficient of determination (0.9812) was obtained.

Sustainability performance of sisal fibre-reinforced CS concrete

CS waste accounts for a large volume of agricultural solid waste in India, and its disposal is a serious problem to the local environment. When CS is used in concrete production, it offers an effective methodology for its disposal and preserves granite, which is a rapidly depleting resource. When fly ash, which is a type of industrial waste, is used in concrete production, the depletion of limestone (a natural resource used for cement manufacturing) is minimised. Thus, the sustainability facet in the construction industry can be improved. This study will help save limestone for future generations and reduce the release of greenhouse gases, such as CO_2 and NO_x, into the atmosphere. The addition of natural fibre enhanced the strength properties of CS concrete with fly ash, and this type of concrete may be used for structural applications. Therefore, the development of sisal fibre-reinforced CS concrete with partial replacement of fly ash will contribute to the sustainability of concrete production.

Conclusion

The influence of adding up to 4.0% sisal fibre based on the weight of cement with 1% increment on the mechanical characteristics of CS lightweight eco-friendly concrete was investigated. The fibre addition reduced the slump of fresh concrete mixture and hardened concrete density slightly. The compressive strength and split tensile strength were improved up to 6% and 14%, respectively, for the fibre dosage of 3%. It also significantly improved the flexural strength. Modulus of elasticity of concrete was slightly improved. A substantial increase in impact energy was achieved for the fibre addition. Additionally, it was found that split tensile strength, modulus of elasticity and flexural strength could be correlated with compressive strength.

CS concrete with partial replacement of fly ash can be used as an eco-friendly building material because CS is a renewable and naturally available resource while fly ash is a type of industrial waste. The addition of sisal fibre addition further enhanced the mechanical properties of CS concrete, thereby making it feasible for structural applications.

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