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Mechanical and durability properties of sisal-Nylon 6 hybrid fibre reinforced high strength SCC

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HIGHLIGHTS

- Improvement of mechanical and durability properties of SCC by natural-synthetic hybrid fibers.
- Hybridization take care of the synergetic action of both fibres.
- Sisal fiber and Nylon 6 are used as natural and synthetic fibers.
- Observed increased performance in strength and durability by hybridization.

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ABSTRACT

The higher paste volume in Self Compacting Concrete (SCC) makes it susceptible to have higher creep coefficient and cracking. Microcracks which are developed during the process of hardening of concrete makes the composite weak. This inherent internal flaw in concrete can be healed by blending it with fibre. A single fibre may be competent only for a narrow range of strain and crack growth rate, hence, may be ineffective for the comprehensive improvement of strength or ductility of concrete. This emanates in Hybrid Fibre Reinforced Concrete which acquires the advantages from the synergistic action of blended fibres. In this study, high strength SCC is developed with sisal-Nylon 6 mono and hybrid fibre combination proportioned at 0/100, 25/75, 50/50, 75/25 and 100/0 of total fibre volume. It is observed that hybridisation improved the flexural and tensile properties vis-à-vis mono fibre mixes. Also the stress-strain and ductility behaviour are augmented by hybridisation. The developed fibre reinforced concrete underwent acceptable water absorption and prevents chances of fibre deterioration which affect concrete durability. Even though nylon enhances mechanical properties it induces durability issues when exposure is considered. A statistical analysis using ANOVA is carried out to prove the effectiveness of hybridisation and fibre volume on mechanical properties of hybrid fiber reinforced self-compacting concrete.

1. Introduction

Self-compacting concrete or Self-consolidating concrete is defined as a concrete with fluid and viscous properties, which can be placed in the mould without any compacting effort. Lack of vibration in SCC yields higher compressive strength due to a better aggregate-paste interface vis-à-vis normal vibrated concrete. Nevertheless, the larger paste volume in SCC makes it susceptible to bigger creep coefficient and cracking. The presence of microcracks which are developed during the process of hardening of concrete makes the composite weak. When subjected to loading, these microcracks coalesces developing weaker planes along which concrete fails. Moreover, micro cracks lead to increased permeability and reduce the durability of the composite.

The concept of the fibre-matrix composite is not new and gaining popularity in today's construction sector. Straws have been used by the Egyptians to reinforce mud bricks before 5000 years. The idea of strengthening concrete with fibre is postulated by Portar in 1910. Bridging and arresting of crack propagation by addition of fibre significantly reduced dry shrinkage characteristics. The stress-strain relationship of hardened concrete shows better results when fibres are incorporated [4]. Also, the ductility is considerably increased with fibres. Presently, the cellulose or natural fibres have evolved into the arena of fibre reinforced composites due to their copious advantages in comparison to the synthetic counterpart. Natural fibres are superior with respect to low cost, less density, specific resistance, renewability, mechanical proper-

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ties etc. Aerospace industries, automotive industries and civil engineering industries are identified as the potential sectors where natural fibre reinforced composite could find pertinence [16]. Ahmed Belaadi et al. [34] investigated the tensile fatigue behaviour of sisal fibres where a slight softening during failure is observed after a brittle behaviour with a sudden decrease in load. Endurance limit for sisal fibre has been established by conducting tests on several samples. Sisal has also proved to be beneficial with its post-cracking flexural capacity in an investigation conducted by Paulo et al. [35] which shows the capability of short sisal fiber in reinforced recycled concrete blocks for one-way precast concrete slabs. The potential of sisal fibre fabric for structural retrofitting is a space that has to be explored. Senthilkumar et al. [37] reviewed the mechanical properties of sisal in polymer composites and observed an enhancement in mechanical properties with the inclusion of sisal fibres. The enrichment in mechanical properties with the hybridisation with synthetic fibres is acknowledged by consolidating the available research studies. Akhila et al. [36] has made an endeavour to evaluate the capability of glass-sisal fibre hybrid system in retrofitting concrete cylinder. Enhancement in axial compressive behaviour, energy absorption and stress-strain response are observed with glass fibre fabric combination. Natural fibres are equally efficient vis-à-vis the synthetic counterparts in terms of mechanical properties. However, as far as durability and fibre-matrix bond is concerned the presence of hydrophilic hydroxyl groups in natural fibres creates several problems at the fibre-matrix interface. Pectin and waxy substances slow down the interlock with the matrix [11]. Reinforcing performance and durability of natural fibres are found to be influenced by their water absorption. Water absorbed by fibres during mixing and casting process is grabbed back partly by cement hardening process to form highly alkaline pore solution which deteriorates the natural fibre [15]. Hence, the fibre surface has to be refashioned with various chemical treatments, coupling agents and reactive additives [11]. Larger water absorption affects the composite durability and service life. Several promising treatment methods of natural fibre for surface modification have been developed. Alkali-treated sisal fibres have resulted in better mechanical properties than silane and heat treated fibres. The enhancement is found to be the maximum for the fibre composite with fibres treated with 4% NaOH [7]. The fibre framework gets modified with the alkali treatment by removal of the amorphous constituents on the fibre so that fibre crystallinity increases [8]. Alkali treatment eliminates microvoids making the fibre surface more uniform and enhances the effective surface area for improved adhesion [11]. SEM microscope study has indicated the benefaction of sisal fibre in the crack arrest and bridging mechanism [13]. The interface delamination and change in the crack path produces a crack deflection mechanism which steers to a ductile composite in flexure and tension. Hybridisation of fibers refer to simultaneous utilisation of efficacious mechanical properties of two or more fibres in a composite. Hybrid fibre reinforcing extensively enthrals vis-à-vis mono fibre reinforcing because of its improved performance with respect to ultimate strength, strain capacity and strain hardening properties [5,6]. Hybridization of fibres can be achieved by combining fibres with varying length, diameter, modulus and tensile strength. When fibres of different moduli are added up the stiffer fibre provides ultimate strength whereas the flexible fibre gives rise to improved toughness and strain capacity. The synergistic combination of hybrid fibre in concrete matrix is better achieved when the fibres are proportioned in such a way that uniform dispersion is attained. In Fig. 1, the bridging effect of macro and micro fibres are represented during loading. On one hand, the lengthier fibres are capable of bridging larger and wider cracks; on the other the micro fibres arrest the microcrack propogation and substantially augment the strength of the matrix.

Hybrid Fibre Reinforced Self-Compacting Concrete (HFRSCC) manifests ductile behaviour with significant residual strength capacity over larger compression strains [9]. HFRSCC specimens possess higher toughness than SCC specimens. Fibre selection, matrix selection, fibre dispersion, fibre orientation, interface strength, porosity and manufacturing process are the main factors that influence the mechanical properties of the composite [10]. Recent investigation has produced zealous outgrowth with hybridisation of natural fibres for reinforcement. Successful outputs have been obtained when natural fibres are blended with polymer fibres. Substantial improvement of mechanical properties of concrete matrix have been observed with addition of fibres. Polymer fibres which are flexible vis-à-vis natural counterpart yields a better uniform dispersion in concrete matrix. Moreover they can augment the consistency of the concrete in fresh state by controlling bleeding and segregation. An enhancement of split tensile and flexural strength along with toughness index is observed by addition of nylon fibres [12]. In flexure, the nylon fibre reinforced beam has continued in contact at maximum load and the crack was comparatively short. The crack-tip stress concentration is reduced by a blunting process because of the debonding crack which inhibits the further crack propagation [14]. Enhancement of composite toughness by accomplishing the desired degree of fibre efficiency possesses relevance with energy absorption, crack control and durability [18]. Recent developments in the canvas of natural fibre reinforcement are catalogued as cellulose fabric reinforcement, internal curing agent, durability enhancers and cellulose nano-reinforcement. Natural fibre reinforced composites find established application in low-cost housing and energy conservation [17]. Apart from this the introduction of supplementary cementitious materials can improve the durability characteristics of SCC [22].

Despite the fact that many studies have done on the synergistic effect of different hybrid fibre combination, there is a limited study on Hybrid Fibre Reinforced Self Compacting Concrete (HFRSCC) with natural-polymer hybrid fibre. Available experimental works ratify the vast potential of sisal fibre in enhancing the mechanical properties of concrete. The best results are obtained when it is deployed with a polymer counterpart. Energy absorption capacity, post crack behaviour, stress-strain response, fatigue behaviour, retrofitting ability etc are found to be reassuring sisal as a choice of deployment. The main disadvantage of sisal fibre, as being a natural fibre, is its excessive water absorption which steers to reduced durability and deterioration of composite. Alkali treatment can enthral the endurance of fibres by surface modification.

In the present work, sisal fibre is used as natural fibre which is having high tensile properties and low elongation (strain). To overcome the drawback of low ductility, sisal fibre is hybridised with Nylon 6 fibre. Performance of SCC in both mono, as well as hybrid fibre combination, is analysed and studied. Designing of an SCC mix is a tedious process which involves proportioning the constituents along with several trials to verify the workability and flow parameters. These parameters of SCC mix in the fresh state is measured by various methods. Fibre addition to SCC mix enhances its tensile and flexural properties but significantly disturbs the flow. Durability limit states are pre-eminently perceived as a relatively new category of serviceability limit state. A focus on qualitative durability studies are carried upon FRSCC which can aid a performance-based design to identify and calculate required design parameters viz. the service life, concrete cover, quality of concrete for severe moisture and acidic exposure. Reliability level of concrete can be qualitatively illustrated by the probability of failure due to exposure effects. Present work focuses on a balance among the performance and durability aspects which can yield the best mix with fresh, hardened and durability properties.

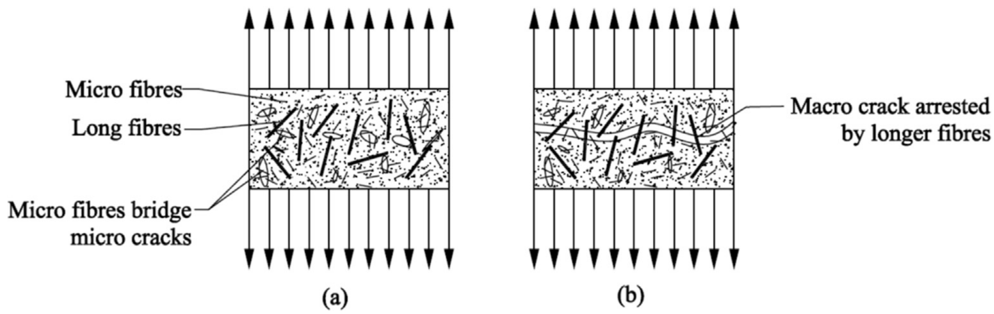

Fig. 1. Fibre action with different lengths (a) Initial Phase (b) Final phase of loading.

2. Materials

Portland Pozzolana Cement (PPC) of ACC brand confirming to IS 1489 (Part I) – 2005 [24] is used. River sand confining Grading zone I of IS 383–2016 [25], passing through 4.75 mm sieve is used as fine aggregate. The gradation curve of fine aggregate is given in Fig. 2. Crushed rocks confirming to IS 383–2016 [25] are used as coarse aggregate. Aggregates of size ranges from 12.5 mm to 10 mm and 10 mm to 4.75 mm in the ratio 60:40 by weight are taken for a denser and uniform mix by trial mixes. Potable water of pH range 7–8.5 is used for mixing the concrete. The natural fibre used in the work is locally available Sisal fibre procured from Coimbatore. The fibres obtained are of long strands of length 750 mm approximately as shown in Fig. 3. Fig. 4 shows the fibres that are cut into 25 mm length and kept for alkali treatment with 4% NaOH [7] before adding into concrete. Water absorption is done to assess the water content correction to be given for SCC mix. Specific gravity test has been conducted to ensure the fibre quality after treatment. Nylon 6 (fibre length 18 mm) is used in combination with sisal. Master Glenium SKY 8233, a new generation chemical admixture based on modified polycarboxylic ether (PCE) is used to prepare the mix at a lower water-cement ratio. The dry material content of superplasticizer is found out according to IS 9103 – 1999 [31]. The physical properties of materials used are listed in Table 1. Table 2 lists the mechanical properties of fibres used.

Fig. 3. Long Sisal Fibres procured for experiment.

3. Methodology

3.1. Mix proportions

A control mix of high strength SCC is prepared to achieve a target strength of 60 MPa. As per EFNARC guidelines [1], a general mix design procedure is not available for proportioning the constituents of SCC. Repetitive trial mixes are done to fix the water-cement ratio and superplasticizer dosage [1,2,3,4,23]. The propor-

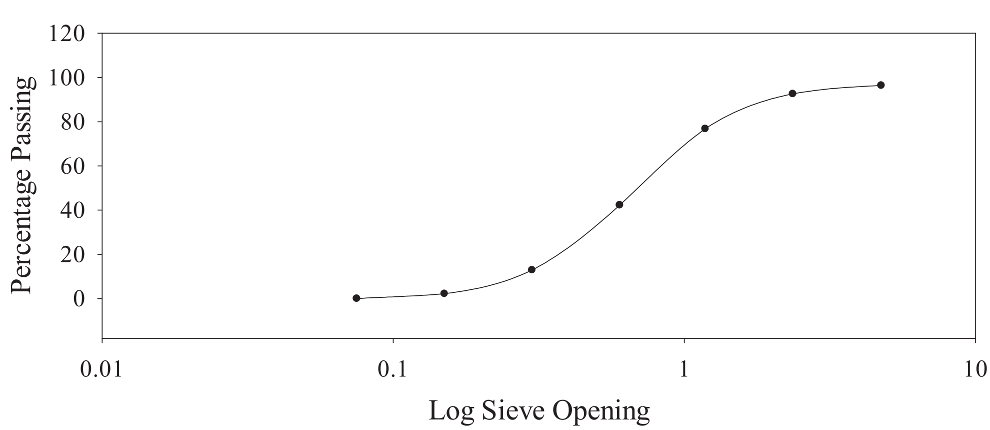

Fig. 2. Gradation Curve of Fine Aggregate.

Fig. 4. Fibres cut into 25 mm length kept for alkali treatment with 4% NaOH.

tions of the component material are obtained with iterative trial mixes and the mix workability parameters are checked with the EFNARC guidelines. The coarse aggregate (CA) size range of 12.5–10 mm and 10–4.75 mm with a proportion of 60/40% of the weight of CA shows better segregation resistance and uniform mix than 100% of 12.5–10 mm size range. The total binder content is fixed as 600 kg/m^3 after iterative mixes to obtain targeted strength. The details of control mix are listed in Table 3. The mixes are compared and examined for both fresh and hardened properties.

3.2. Preparation of hybrid fibre SCC

Control mix of SCC is fixed by conducting iterative trials and comparing the fresh properties with EFNARC Guidelines. Fibre addition has caused a significant reduction in workability and flow. Hence, it is found crucial to determine the maximum fibre content that can be added so that the workability and flow remain within acceptable limits. Once the control mix for SCC has been fixed, trial mixes for fibre reinforced SCC is conducted. SP dosage has been increased through 0.1% to the fibre added mixes to retain the workability properties. By trials, it is found that the limiting fibre volume for the mix was 0.375% volume fraction for FRSCC. Mono-fibre reinforced SCC with Nylon 6 and sisal fibres at 0.1, 0.2, 0.3 vol% fraction is prepared. Sisal fibre is added with Nylon 6 to make hybrid combinations with 25/75, 50/50, 75/25% of fibre volume.

3.3. Mix nomenclature

All the fibre reinforced mixes are named as T-S/N, where T = total fibre volume, S = percentage of sisal in total fibre volume and N = percentage of Nylon 6 in total fibre volume. For example, 0.2–75/25 is a mix with 0.2% fibre by volume with 75% sisal and 25% nylon. Control mix is denoted as "0–0/0".

3.4. Specimen preparation

Following are the details of set of specimens prepared for the study

Cube: 150 m × 150 mm × 150 mm
Cube: 100 mm × 100 mm × 100 mm
Cylinder: 100 mm diameter × 200 mm height
Cylinder: 200 mm diameter × 300 mm height
Flexure beam: 100 mm × 100 mm × 500 mm

Specimens are cast for mono-fibre reinforced SCC with Nylon 6 and Sisal at 0.1, 0.2 and 0.3% of total volume, and the hybrid combination of Sisal with Nylon 6 with 25/75%, 50/50% and 75/25% of total fibre volume fraction.

Table 1
Properties of materials used.

Material	Property	Test Result	Test Reference
Cement	Specific Gravity	3.05	IS 4031 – Part 11 [30]
	Normal Consistency	35.5%	IS 4031 – Part 4 [28]
	Initial Setting Time	120 min	IS 4031 – Part 5 [29]
	Final Setting Time	250 min	IS 4031 – Part 5 [29]
Fine Aggregate	Specific Gravity	2.55	IS 2386 – Part 3 [27]
	Water Absorption	1.03%	IS 2386 – Part 3 [27]
	Sieve Analysis	Zone I	IS 2386 – Part 1 [26]
	Fineness Modulus	2.76	IS 2386 – Part 1 [26]
Coarse Aggregate	Specific Gravity	2.67	IS 2386 – Part 3 [27]
	Water Absorption	1.07%	IS 2386 – Part 3 [27]
	% Voids in loosely piled CA matrix	49.19%	Nan Su, 2001 [2,3]
Super plasticizer	Solid Content	30.77%	IS 9103 – 1999 [31]
Sisal Fibre	Water Absorption	176%	–
	Specific Gravity	1.2	–
Superplasticiser	Aspect	Reddish Brown liquid	–
	Relative Density	1.08 ± 0.02 at 25 °C	
	pH	≥6	
	Chloride ion Content	<0.2%	

Table 2
Mechanical Properties of Fibres.

Fibre Name	Density g/cm3	Modulus of Elasticity GPa	Tensile Strength MPa	Elongation at break %	Reference
Sisal	1.3–1.5	9–22	600–700	2–3	[5,10,17,18]
Nylon	1.14	2.5–5.17	750–1000	15–30	[5,14]

Table 3
Details of Control Mix.

Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	W/C	SP (%)
600	978.55	736.79	0.34	0.4

4. Experimental investigation

4.1. Fresh stage properties

As per EFNARC guidelines, no single or combination of methods have been found out which can uniquely characterise all the rheological properties of self-compacting concrete. Fresh stage concrete tests like Slump flow test, T50 test, V funnel time test and L Box test have been conducted on the fresh concrete to assess the workability parameters of SCC after addition of different fibre combinations.

4.2. Hardened stage properties – mechanical properties

Compressive strength test is conducted on 150 mm × 150 mm × 150 mm cubes and cylinders with 100 mm diameter and 200 mm height cured for 28 days in a compression testing machine of capacity 2000 kN. The load has been applied on a face perpendicular to casting face of cubes. Split tensile strength test is conducted on cylinders with 100 mm diameter and 200 mm diameter in a compression testing machine of capacity 2000 kN and load applied diametrically. Flexural strength test is conducted on unreinforced beams of size 100 mm × 100 mm × 500 mm by four-point loading. Stress–strain relationship test is conducted on cylinders with 150 mm diameter and 300 mm height where the axial strain has been measured with a compressometer of least count 0.01 mm.

4.3. Durability studies

4.3.1. Water absorption test

Cube specimens of size 100 mm × 100 mm × 100 mm have been used for water absorption test. The cubes are oven dried for 24 h at 110 °C to obtain a constant weight. The specimens are then immersed in water completely. The weights are measured at different time intervals of 15mins, 1 h, 3 h, 6 h, 24 h and 7 days. Water absorption is calculated as percentage increase of moisture content with respect to oven dry weight.

4.3.2. Acid durability test

Cube specimens of size 100 mm × 100 mm × 100 mm have been used for acid durability test. The cubes are immersed in 2% Hydrochloric acid for 30 days and 60 days. Durability is assessed as a measure of mass loss and compressive strength loss with reference to normal control specimens.

5. Results and discussions

5.1. Fresh stage properties

Table 4 presents the fresh stage properties of the different mixes and observed that the workability parameters are within EFNARC guidelines. Fig. 5 shows the flow of SCC control mix. Fresh concrete results are in agreement with the results reported by previous researchers [4,12]. Test results show that the increase in fibre volume reduces the workability as a result of moisture absorption by hydrophilic natural fibres [17]. Flowing ability is also considerably reduced at higher fiber volume fractions [4,12]. A substantial reduction in workability of cement concrete is reported. Hybrid fibre mixes offer better flow than mono sisal fibre mixes due to the flexible nature of nylon fibre. It has been observed from the trial mixes that the maximum permitted fibre volume for the control mix in terms of workability is 0.375%. Hence, in the present study, to retain the flowability, fibre volume has been limited to 0.3% and SP dosage has been increased to 0.5%. Sisal fibre being stiff offers a reduced L Box value due to reduced passing ability. Even though the addition of fibres in SCC reduces flowability and passing ability, polymer fibres improve the stability of SCC by arresting the settlement and cracking due to plastic shrinkage [1]. Nylon fibre has made the mix uniform with improved stability and controlled segregation.

5.2. Hardened properties

5.2.1. Cube compressive strength

Fig. 6 shows assembly for testing the cube compressive strength for different mixes. The test results are shown in Fig. 7 for different mixes. The decreased compressive strength has been inferred due to the heterogeneity of mix at higher fibre volume [12]. The results

Table 4
Fresh Stage Concrete Properties.

Mix Name	Slump Flow (mm)	T50 (s)	V Funnel Time (s)	L Box Test
0–0/0	750	1.96	8.03	1
0.1–100/0	740	2.15	9.51	0.95
0.2–100/0	700	3.32	10.18	0.82
0.3–100/0	645	4.06	11.41	0.75
0.1–0/100	720	2.07	9.2	0.98
0.2–0/100	695	3.92	10.24	0.86
0.3–0/100	635	4.51	11.82	0.77
0.1–25/75	700	2.49	9.14	0.91
0.1–50/50	690	2.25	9.26	0.89
0.1–75/25	685	2.61	9.24	0.86
0.2–25/75	670	3.9	10.26	0.8
0.2–50/50	660	3.56	10.34	0.78
0.2–75/25	665	3.87	10.55	0.79
0.3–25/75	640	4.43	12.15	0.8
0.3–50/50	660	4.3	11.8	0.79
0.3–75/25	675	4.28	11.78	0.78

Fig. 5. Flow of SCC control mix.

Fig. 6. Cube testing by compression testing machine.

have revealed that an increased fibre volume results in reduced compressive strength. Nevertheless, a small volume fraction of 0.1% can enhance the compressive strength. Among all the hybrid volume fractions, a hybridisation ratio of 50/50 has come forth with maximum strength.

5.2.2. Cylinder compressive strength

The cylinder compressive strength corresponding to different mixes are given in Fig. 8. Cylindrical specimen of concrete reinforced with nylon fibre when subject to an increasing compressive load causes crack initiation and propagation due to lateral tension. Debonding occurs at the fibre-matrix interface due to a normal tensile stress to the anticipated path of crack advancement. The crack-tip stress concentration is hence reduced by a blunting process because of the debonding crack which inhibits further crack propagation. Compressive strength is found to increase due to this blunting, blocking and crack diversion [14]. Cylinder strength decreases with increased fibre volume. A hybridisation of 50/50 renders better strength.

5.2.3. Split tensile strength

Figs. 9 and 10 shows the specimen assembly for split tensile strength testing and results of test conducted on cylindrical specimens of differing fibre volume and hybridisation respectively. Splitting tensile strength is found to set out a better performance vis-à-vis plain concrete [14]. Split tensile strength increases with an increase in fibre volume. The sisal-Nylon 6 hybridised mixes are found superior vis-à-vis mono fibre mixes. A 75/25 mix has resulted in increased split tensile than a 100% sisal mono fibre reinforced mix.

5.2.4. Flexural strength

A schematic representation of the loading assembly for four point flexural loading is shown in Fig. 11. Fig. 12 shows the results of four-point bending test for various fibre volumes and hybridisation. The synergistic effect of crack bridging by fibres and strain redistribution across the beam cross-section enhances the HFRSCC specimens to maintain its strength improvement in a ductile habitude. The investigation has revealed that hybrid fibre redistributes the strains in reinforcing bars and arrests the splitting crack development at intermediate strain levels beyond yielding [9]. 25/75 hybridised mixes accrue improved flexural strength than mono fibre mixes. Even though 75/25 and 50/50 hybridised mixes have resulted in a reduced flexural strength, the hybrid combination mixes yielded a better performance than a 100% solo fibre mix.

5.2.5. Stress-strain relationship

Figs. 13–15 shows the stress-strain behaviour of fibre reinforced specimens with volume fractions 0.1, 0.2 and 0.3 respectively when subjected to an axial compressive load. The P-δ behaviour of the hardened concrete shows improved results when fibres are incorporated [4]. Also, the ductility is considerably increased with fibres. The specimens cast out of HFRSCC have not exhibited any spalling behaviour until approaching 3% strain levels [9]. The stress-strain relationships for different fibre volumes and hybridisation ratio showed that the ductility has increased to a larger extent as the proportion of Nylon 6 increased. Nevertheless, the stiffness at higher volume fraction get reduces due to larger nylon proportion. Smaller fibre proportions improved the stiffness of the mix. Hybridisation has a noticeable effect in improving the ultimate strain and ductility. Exceeding the optimum fibre volume can impede the mechanical properties due to uneven load transfer in the composite [37]. This might be the reason for reduction in stiffness of the composite at increased fibre volume.

5.3. Durability studies

5.3.1. Water absorption

Fig. 16 shows the test result of water absorption of the concrete specimen by the passage of time. Addition of fibres both in mono and hybridised stage increases the water absorption of concrete. The initial water absorption immediately after immersion is found to be independent of fibre volume. Nevertheless, the water absorption after 7 days is exclusively dependent on fibre volume and hybridisation ratio. From the results obtained, it can be observed that Nylon 6 plays an important role in increasing water absorption vis-à-vis a mono fibre sisal mix. Nylon, when heated to 110 °C to oven dry, crosses its glass transition temperature and may act as a soft plastic medium which can absorb 10% of water.

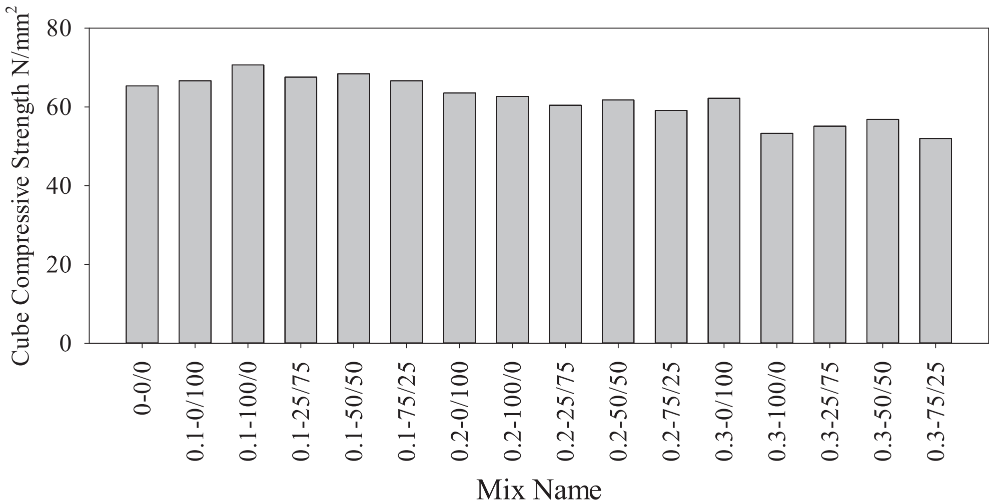

Fig. 7. Cube Compressive strength of different mixes.

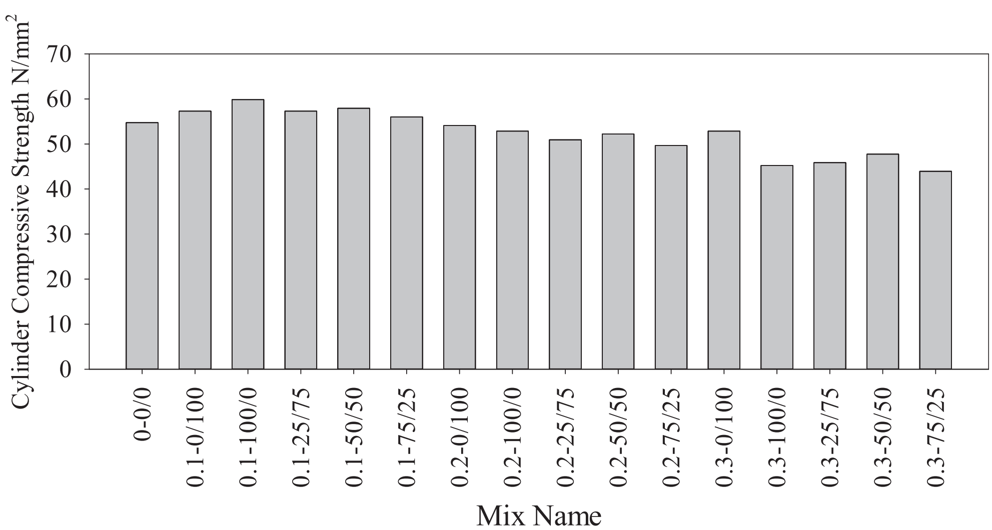

Fig. 8. Cylinder Compressive strength of different mixes.

This may be the reason for increment in water absorption for nylon rich mixes. Out of the hybridised mixes, 75/25 shows a better performance in water absorption. High moisture absorption and poor bonding properties of natural fibres are identified as a hurdle for their multifarious application in structures [16]. The water absorption percentages are well below the acceptable values. The concrete matrix designed is dense and impermeable that there is no considerable increase in water absorption vis-à-vis the control mix.

5.3.2. Acid durability

The experiments conducted by Pengfei Huang et al. [19], A K Al Tamimi et al [20] and Paraic et al [21] have authenticated that the compressive and flexural strengths and elastic modulus of concrete are strongly affected by surface corrosion caused by HCl solution. The degree of deterioration increased with HCl content. The chemical reaction between the cement paste and HCl made the surface of the specimens rough after completion of the exposure period. Acidic solution increased the porosity of concrete structure.

Strength loss and mass loss are observed in the experimental results due to the exposure of concrete specimens to 2% concentrated HCl acid lead. $CaCl_2$ formed from the reaction of $Ca(OH)_2$ in hydrated cement paste with HCl makes the concrete surface porous. The chemical reaction is

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O$$

The water-soluble salt easily migrates to the outlying regions of concrete. The unceasing reactions enhanced the porosity of cement paste and the enlarged pore volume boosts the rate of reaction. This may be the reason for surface roughening and mass loss. High strength concretes are more susceptible to HCl attack than normal concretes [19–21].

Figs. 17 and 18 shows the percentage mass loss and percentage strength loss for 30 days and 60 days respectively. Mono fibre mixes of sisal are found to be more resistant to HCl attack. They have experienced little deterioration vis-à-vis hybrid mixes. It may be due to the surface modification of sisal by alkali treatment which has made it inert. From the observations, Nylon 6 rich mixes have showed a larger strength loss at 30 and 60 days. Nylon is moderately soluble to insoluble in acidic media and may display zwitterionic behaviour or tensio-active properties in acidic medium. A zwitterion is a bipolar molecule which carries functional groups of opposite charges and as a whole does not possess any charge. This can reduce the surface tension of the fluid and

Fig. 9. Split tensile strength testing.

enhance the acid attack more into pore spaces. This may be the rationale for considerable strength loss in nylon rich mixes for a particular fibre volume. Also, fibre volume plays a crucial role in strength loss. Deteriorated fibre spaces may intensify acid attack by more exposed interior surface area.

As far as the mass loss is considered, 30 days mass loss is observed to be dependent upon the fibre volume and hybridisation. Again nylon rich mixes have showed a larger mass loss. This may be due to the dissolution of CSH and $Ca(OH)_2$ into the acidic solution. However, mass loss by 60 days exposure of cubes in acidic solution is found independent of fibre volume. As the cubes are stored in a static fluid, the CSH and $CaCl_2$ dissolution may have retarded and deposits may have occurred inside the pore spaces. These deposits which get trapped in the pores may be the reason for the little variation in masses of the specimen. Also, it can be inferred that the nylon may have undergone drastic deterioration in 60 days time and sisal being more resistant to HCl due to prior surface treatment which have made the pore space intact [33].

6. Statistical analysis

Analysis of variance or ANOVA is a basic statistical model which depicts a statistical relationship between the predictor and response variable. The concept is to test differences between two or more means. A probability distribution is identified corresponding to each factor level. The analysis proceeds in two basic steps

- Determine if the factor level means vary
- Examination of how the factor level means differ and implications of variation of factor level means

ANOVA does not test any specific differences but a general difference among means. It tests a non-specific null hypothesis also known as an omnibus null hypothesis for equality of population means. The conclusion from a rejected omnibus null hypothesis is that at least one population mean is different from at least one other mean.

ANOVA calculations are done for inspecting statistically the effect of hybridisation and fibre volume on mechanical properties. The null hypothesis is proposed as hybridisation and fibre volume do not have any individual and interaction effect on mechanical properties or the means are equal. The analysis was conducted at each fibre volume level for different hybridisation ratio.

Kutner et al. [32] proposes ANOVA factor effects model as,

$$Y_{ijk} = \mu.. + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}$$

With null hypothesis H_0 : all $(\alpha\beta)_{ij} = 0$, for all i,j @ 95% confidence

Alternate hypothesis H_a : not all $(\alpha\beta)_{ij}$ equal zero

Null hypothesis is rejected when, test statistic $F^* > F^{\alpha}[1-\alpha; (a-1)(b-1), (n-1)ab]$

Table 5 shows the analysis summary for different mechanical properties. The test statistic F^* is found to be greater than F^{α} which concludes a rejection of the null hypothesis. The substantial effect of fiber volume and hybridisation in the mechanical properties is statistically proved from the investigated specimens.

7. Conclusion

Self-compacting concrete is one of the revolutionary innovations that man has ever made in the construction sector. It is first introduced in Japan due to the scarcity of skilled labour. Neverthe-

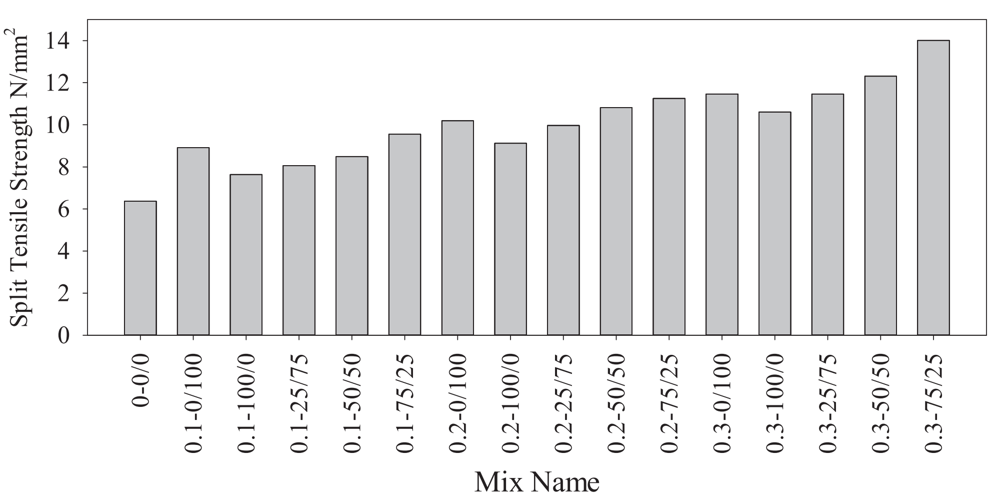

Fig. 10. Split tensile strength of different mixes.

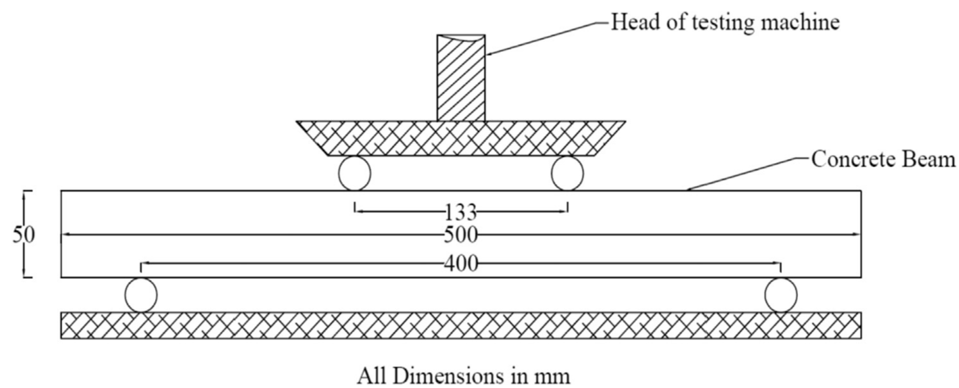

Fig. 11. Schematic representation of Loading assembly for four point flexural loading.

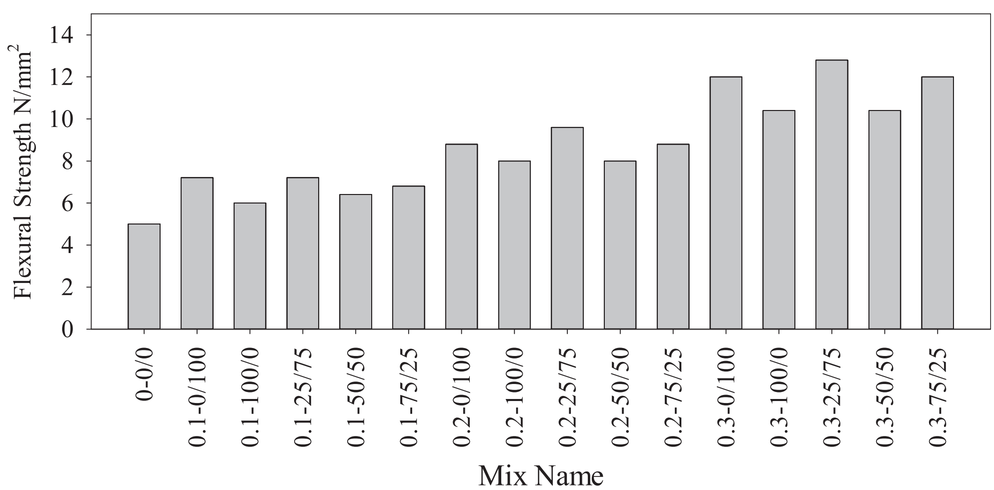

Fig. 12. Flexural Strength of different mixes.

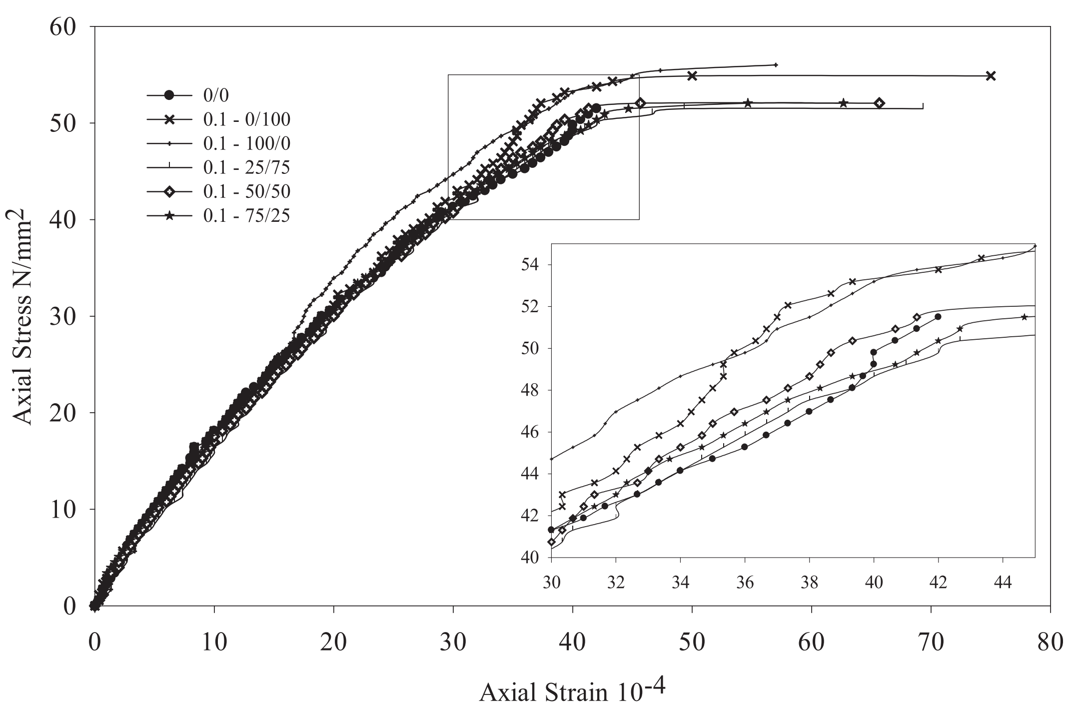

Fig. 13. Stress-Strain Relationship for Volume fraction 0.1%.

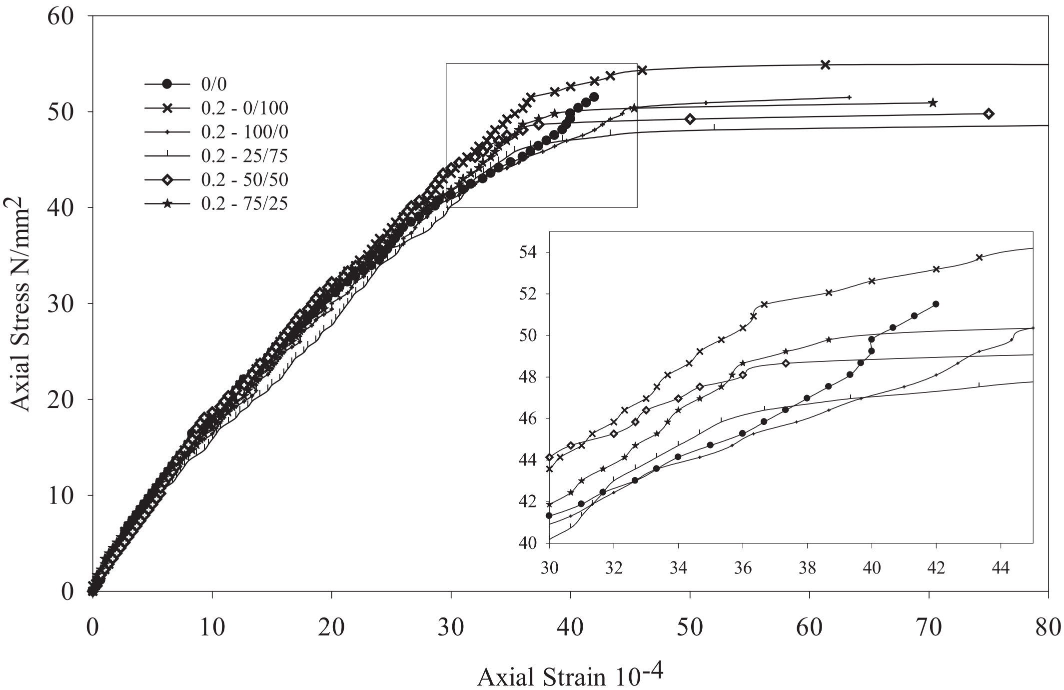

Fig. 14. Stress-Strain Relationship for Volume fraction 0.2%.

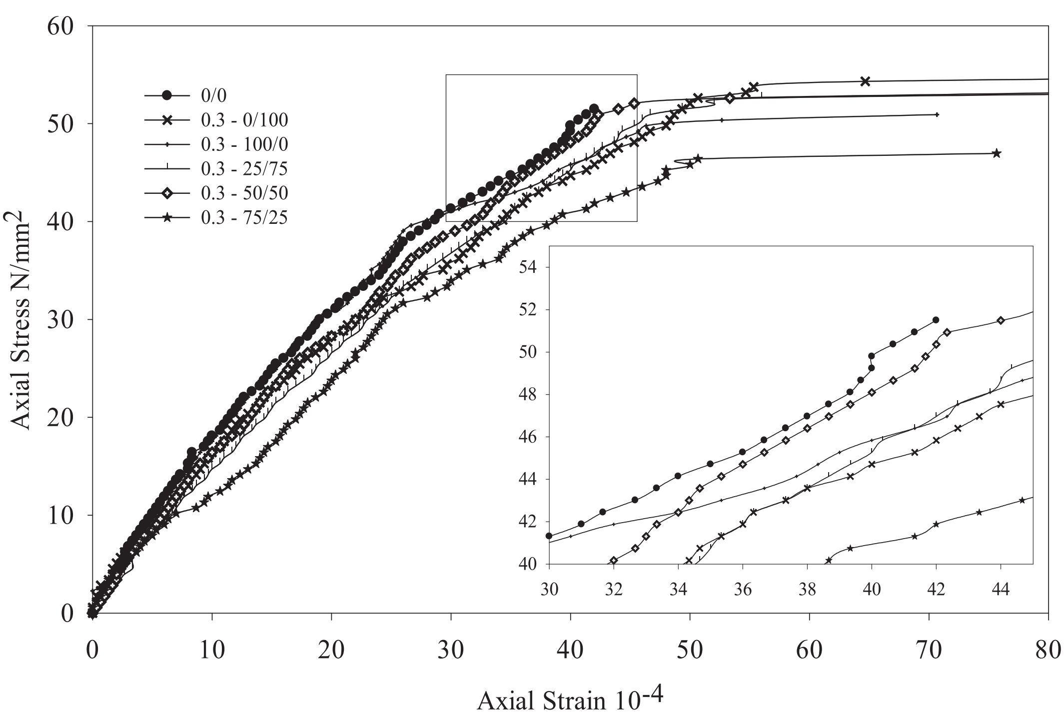

Fig. 15. Stress-Strain Relationship for Volume fraction 0.3%.

less, SCC, presently, highly endorse for faster construction, improved durability, thinner concrete sections, improved surface finish etc. The synergistic ascendancy that fibre illustrates with concrete in both strength and ductility further augments the developments in concrete technology. Hybridising fibres confederate the leverage of both.

In this study, the effect of hybridising sisal with Nylon 6 in SCC is studied. Fibre volume fractions of 0.1%, 0.2% and 0.3% are studied. The fibres are hybridised at proportions 25/75, 50/50 and 75/25 of the total fibre volume. A considerable reduction in workability of cement concrete is reported as a result of moisture absorption by hydrophilic natural fibres. Improvement of cracking of cement composite by plastic shrinking and induced tensile stresses by fibre addition is noticeable. Hardened properties like mechanical strength and durability are analysed. Addition of fibre results in an overall reduction in compressive strength of concrete. The irregular fibre distribution beyond optimum fibre content lead to uneven load transfer in the composite which may be a critical

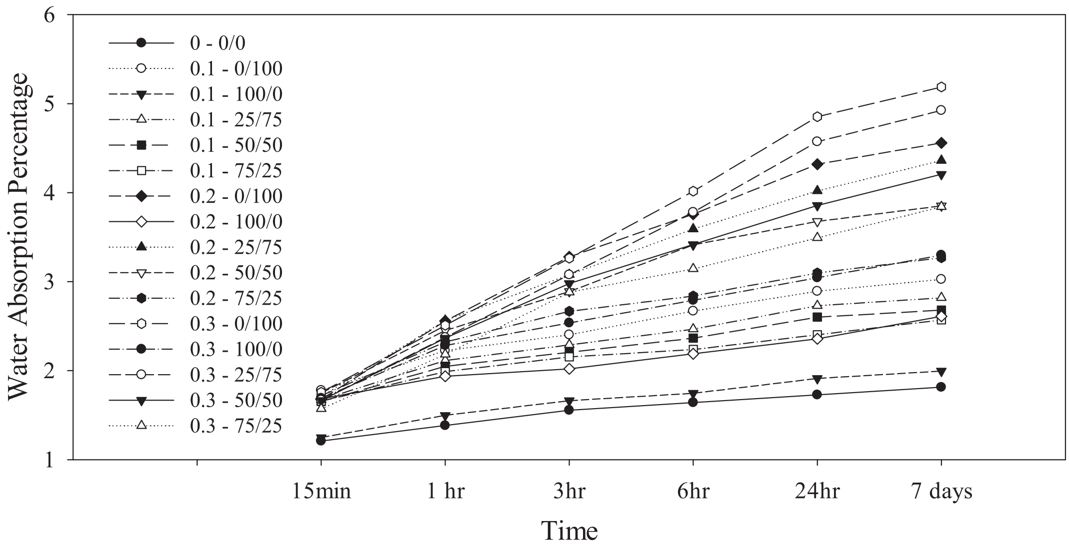

Fig. 16. Water Absorption Vs Time.

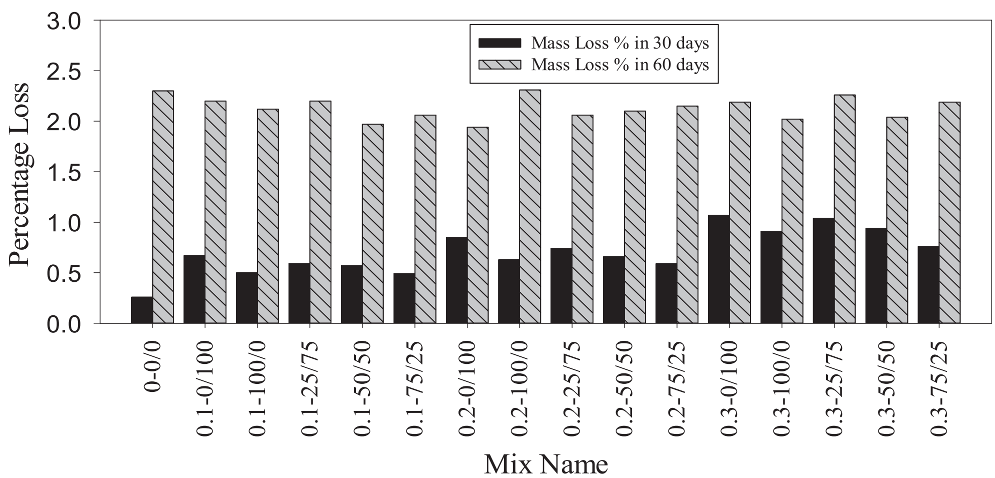

Fig. 17. Percentage Mass Loss by HCl exposure.

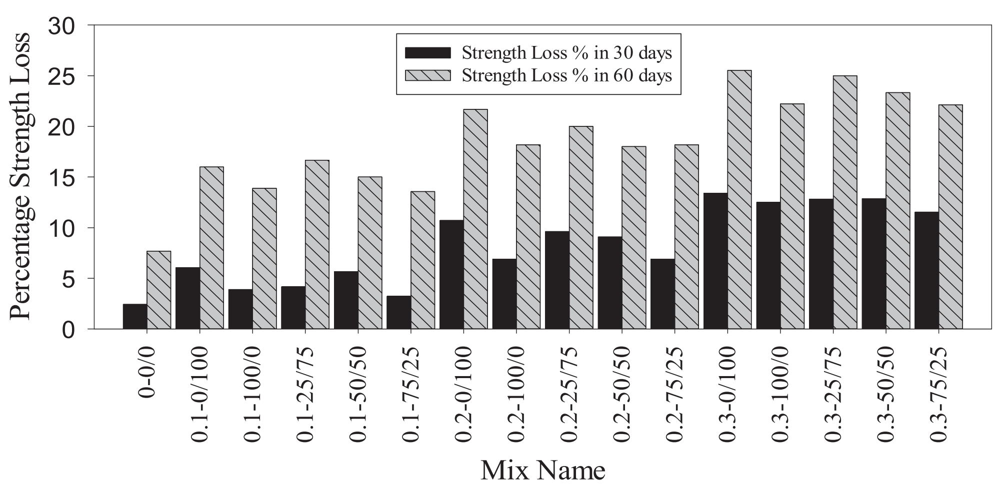

Fig. 18. Percentage Strength Loss by HCl exposure.

factor leading to reduction in the mechanical properties. However, hybridisation seems to improve the ductility which makes it suitable for earthquake applications. Hybrid fibre combinations show better performance than mono-fiber counterparts as tensile and flexural properties are considered. Being the durability of composite an imperative thought in structural design, natural fibres are

Table 5
ANOVA analysis summary for different mechanical properties.

Mechanical Property	Factor	Test Statistic F*	Critical Statistic Fα	Reject Null Hypothesis	Inference
Cube Strength	Fiber Volume	736.32	3.15	YES	Fiber volume has effect
	Hybridisation	39.48	2.53	YES	Hybridisation has effect
	Interaction	24.06	2.1	YES	Interaction has effect
Cylinder Strength	Fiber Volume	564.53	3.15	YES	Fiber volume has effect
	Hybridisation	39.35	2.53	YES	Hybridisation has effect
	Interaction	14.74	2.1	YES	Interaction has effect
Split Tensile Strength	Fiber Volume	214.58	3.15	YES	Fiber volume has effect
	Hybridisation	36.52	2.53	YES	Hybridisation has effect
	Interaction	2.6	2.1	YES	Interaction has effect
Flexural Strength	Fiber Volume	839.02	3.15	YES	Fiber volume has effect
	Hybridisation	47.07	2.53	YES	Hybridisation has effect
	Interaction	3.37	2.1	YES	Interaction has effect

found vulnerable to alkaline pore solution. Hence in the present study, PPC has been used instead of OPC to reduce the alkalinity of concrete matrix which is harmful to sisal fibre. Also, sisal fibre is surface modified with alkali treatment to enhance its durability. A performance based analysis is carried out to qualitatively estimate the deterioration of FRSCC on cases of severe exposure conditions of moisture and acid. Concrete deterioration can be mass loss caused by abrasion, erosion and cavitations and another by temperature and humidity gradients. Although nylon fibre improved the mechanical properties when hybridised with sisal, it is found to be prone to water absorption and HCl attack that affects durability. Caution must be taken during design as far as exposure is concerned. ANOVA analysis has been carried out to statistically prove the effect of hybridisation and fibre volume.

Natural fibres are found to be excellent for secondary structural components with their lightweight, moderate strength and low-cost properties. Excellent resilient and shock absorbing capability steers it into research arena with ample possibilities. Care must be observed during harvest and treatment of natural fibres for increased efficiency. Fibre orientation plays a crucial role in the improvement of mechanical and shock absorbing properties. Also, there are chances of micro void space accumulation due to entrapped air. Despite the overall reduction in the cost of the composite, drawbacks like flammability, inconsistency, high moisture absorption and poor bonding properties of natural fibres are identified as a hurdle for their multifarious application in structures. Most of these drawbacks can be avoided by proper treatment of fibre during the construction stage as well as hybridisation with a proper artificial fibre.

Conflict of interest

None.

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