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Experimental and statistical investigation on synergistic effect of nano based epoxy hybrid FRP on strength and durability of circular concrete columns

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ABSTRACT

Strengthening and retrofitting of concrete structures using fiber reinforced polymer (FRP) wrapping is a promising technique in construction sector. Epoxy is the commonly used matrix which possess a higher rate of degradation under exposure to harsh environment. The evaluation of strength and durability of concrete cylinders confined by multi walled carbon nanotube (MWCNT) incorporated epoxy with hybrid sisal and basalt fiber composite systems exposed to various environmental conditions forms focus of this paper. Specimens are subjected to various environmental exposure such as elevated temperature, acidic, alkaline and sea water conditions. Two varieties of epoxy viz. neat epoxy and MWCNT modified epoxy systems are considered. Mechanical and durability properties are analyzed based on axial compressive behavior, stress strain response, visual inspection and modes of failure. The MWCNT incorporated epoxy based hybrid FRP confined specimens exhibited a strength reduction less than 10% when compared with unexposed confined specimens under aggressive environmental conditions, while unconfined specimens showed strength reduction by 40% when compared to unexposed unconfined specimens. The MWCNT modified epoxy based hybrid confinement showed an energy absorption of 6.24 times that of unconfined specimens upon chemical exposure. Ultrasonic Pulse Velocity test revealed efficacy of confinement system in protecting concrete core from a sudden failure, which in turn increases the compressive strength of system. A statistical analysis using ANOVA was employed to find significance of these factors and confirmed with experimental results. The effect of MWCNT incorporation is significant in FRP confinement and shows the possibility of the FRP system to be adopted as a major retrofitting material in alkaline and sea water environments.

1. Introduction

From the beginning of construction stage to the end of service life, Reinforced Concrete (RC) structures are vulnerable to structural deficits and reparations. In order to ensure structural stability and to maintain safety and serviceability conditions, various strengthening and retrofitting methods were developed over the last few years. To improve the efficiency of conventional retrofitting techniques, extensive investigations were conducted to develop an alternative system. Accordingly, fiber reinforced polymer (FRP) composites have been developed as a promising system for external strengthening of structural systems (Padanattil et al., 2019; de Diego et al., 2022). Easy installation, high tensile strength and resistance to corrosion are the major advantages of FRPs which make them a prominent candidate for structural strengthening. For the purpose of lateral strengthening of RC structures, carbon, glass, aramid and basalt FRP systems were commonly used (Taghia and Abu Bakar, 2013; Toutanji and Deng, 2002; Wu et al., 2009; Trapko and Musiał, 2011). They were found to increase the load bearing capacity and ductility of RC structures. However, the high cost and eco-unfriendly nature of these fibers promotes the development of alternate systems. In order to replace the costly and environmentally

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Abbreviations/Nomenclature

FRP	Fiber reinforced polymer
CNT	Carbon nanotube
MWCNT	Multi walled carbon nanotube
SFRP	Sisal fiber reinforced polymer
HSBFRP	Hybrid sisal and basalt fiber reinforced polymer
CS	Control concrete Specimen
C-E0C2S	Concrete specimen without CNT in Epoxy and 2 layer Sisal wrap
C-E0C2S2B	Concrete specimen without CNT in Epoxy and 2 layer Sisal wrap followed by 2 layer Basalt wrap
C-E1C2S	Concrete specimen with 1 wt% CNT in Epoxy and 2 layer Sisal wrap
C-E1C2S2B	Concrete specimen with 1 wt% CNT in Epoxy and 2 layer Sisal wrap followed by 2 layer Basalt wrap
TEM	Transmission electron microscopy
UPV	Ultrasonic pulse velocity
ANOVA	Analysis of variance

harmful synthetic fiber systems, various natural fiber systems were developed (Pimanmas et al., 2019; Ispir et al., 2018; Ramesh et al., 2013; Siriluk et al., 2018; Hong et al., 2021; Midhun and Radhika, 2015). Further, on hybridization they noticed a synergistic improvement in the final properties of the system. Limited research has been carried out on the hybridization of fibers for structural reinforcement. When compared to individual natural fiber systems, studies on hybrid FRPs including jute, sisal, and glass exhibited superior mechanical and ductility properties.

Epoxy resin is commonly used as an adhesive to bond these hybrid FRP systems onto the concrete surface. Epoxy resin is a thermosetting polymer widely used as the matrix medium in FRP composites. High strength, specific stiffness, high strength to weight ratio and chemical resistance make them suitable as a matrix material (Sarath Kumar et al., 2020). However, exposure to severe environmental conditions for a longer period cause the degradation of the epoxy resin. Incorporation of various nano fillers in traditional fiber reinforced polymer systems not only improves the mechanical properties but correspondingly reduces the aging impact on epoxy resin significantly. Carbon atoms are capable of bonding in many ways. Consequently, they exist as different allotropes of carbon with contrasting properties. The well-known allotropes are graphite, diamond, fullerenes, nanotubes and graphene. While the first two are naturally occurring, different methods are employed for the preparation of the last three. A graphene layer rolled into a tube without seam forms a single walled carbon nanotube (SWCNT). Multiple layers of graphene seamlessly rolled into a concentric tubular structure forms the shape of multi walled carbon nanotubes (MWCNT). MWCNTs are cheaper to produce and hence finds wide application in various industries (Alhareb et al., 2017; Shivakumar Gouda et al., 2017). MWCNT incorporated epoxy resin is also capable of resisting propagation of cracks at various locations in the composite. At higher concentrations of MWCNT, Van der Waals forces of attraction between individual nanotubes may cause agglomeration and decrement in final properties (Sarath Kumar et al., 2021). Hence, it is extremely important to arrive at the optimum content of MWCNT in FRP systems.

Studies have been carried out on the hybridization of natural fibers such as sisal, abaca, jute with glass and reported superior mechanical properties when compared to natural and conventional glass fiber reinforced polymer (GFRP) systems (Padanattil et al., 2017; Vijaya Ramnath et al., 2013). Bouchelaghem et al. (2011) carried out a comparative study between the commonly used FRP systems with hybrid systems and noticed hybrid fiber arrangement offered an economical solution. De Luca et al., 2011 investigated the variation in stress-strain curves post ultimate load in hybrid systems and noticed minor drop in load throughout the strain increments. They also noticed that ductility and energy dissipation can be enhanced on hybrid FRP jacketing. Joseph et al. (2022a) studied mechanical behavior of nano filler incorporated epoxy based hybrid fiber confinement under axial loading and stated that nano filler modification of epoxy was capable of enhancing the mechanical properties significantly.

The investigations on FRP confined concrete columns specify that external confinement is an effective solution for structural strengthening and retrofitting (Wahab and Hussain, 2019). Nevertheless, the durability properties of the FRP confined systems should be addressed before extensive application.Chowdhury et al. (2011) studied the high temperature influence and concluded that it crucially affects the strength, bond and stiffness properties of FRP systems. Synthetic fibers like carbon fibers were capable of resisting temperatures above 800 °C but the epoxy matrix experienced a considerable loss in properties when exposed to elevated temperature (Cerniauskas et al., 2020). The performance offered by epoxy matrix mainly depends on its glass transition temperature (Tg) and during high temperature the epoxy loses its mechanical properties (Chowdhury et al., 2007; Joseph et al., 2022b). A recent study on the durability of FRP confined systems indicated that they reacted with the exposed chemical environments which further affected the performance of fiber within the epoxy matrix and resulted in reduced strength (Mohammedameen et al., 2019). While selecting the type of fiber systems as external confinement, properties such as resistance to corrosion, chemical attack, temperature variation, and wet-dry cycles should also be considered. The extend of progression of damage in concrete were critically assessed with ultrasonic pulse velocity (UPV) (Mini et al., 2014).

It is noticed that a study to explore the mechanical and durability performance of nano filler added epoxy based hybrid natural FRP system wrapped concrete columns is not explored. This study explores the effectiveness of the addition of MWCNT in epoxy to improve the various mechanical and durability properties of the epoxy matrix when used as a FRP confinement during the strengthening/retrofitting of concrete structures. The work focuses on the performance evaluation of columns confined with natural and organic FRP systems like individual sisal FRP (SFRP) and hybrid sisal and basalt FRP (HSBFRP) confined systems. Sisal fibers which are plant based are susceptible for moisture absorption during their service. The presence of inorganic basalt as outer layers is expected to protect inner sisal layers from moisture absorption and other environmental impacts related to thermal cycling, humidity changes etc. The inclusion of sisal is to promote sustainability in construction. Moreover, basalt is also a naturally occurring fiber obtained from rocks. This combination is expected to reduce the consumption of commonly used artificial carbon fiber systems. The behavior of the HSBFRP confined specimens when exposed to various durability conditions separately such as elevated temperature, acid environment, alkaline environment and sea water environment is analyzed in detail with reference to the axial load carrying capacity, stress strain behavior and ductility properties.

2. Materials and methods

2.1. Materials

2.1.1. Concrete

Concrete with a target strength 20 MPa was considered as the inner concrete core. The concrete mixing procedure was carried out according to IS 10262-2009. A mix proportion of 1:1.5:2.58 by weight of cement, fine and coarse aggregate with 0.45 as the water/cement ratio was maintained during the preparation of the test specimens. The cylindrical specimens were prepared and water cured under normal conditions. The standard concrete cylinders were used to perform the various strength tests. Table 1 contains the various material properties adopted.

Table 1
Properties of the constituents in concrete.

Properties	Values
Grade of cement	OPC Grade 53
Specific gravity of cement	3.16 kg/m^3
Fineness modulus of fine aggregate	2.82 mm
Specific gravity of fine aggregate	2.64 kg/m^3
Bulk density of coarse aggregate	1.51 kg m^3
Specific gravity of coarse aggregate	2.65 kg/m^3

2.1.2. MWCNT modified epoxy resin

The two-part epoxy resin composed of resin (LY 556) and hardener (HY 991) was used for the study. The two parts were mixed in 100:15 ratio as per the guidelines of the manufacturer. The nano filler was MWCNT modified carboxylic acid (–COOH) with 97% nanotube purity purchased from Platonic Nanotech Private Limited, Jharkhand, India.

2.1.3. FRP system

As external confinement for concrete specimens, bi-directional sisal fabric of 300 g/m^2 with a density of 1580 kg/m^3 was used as the inner layer. They were subjected to NaOH alkaline treatment to improve surface roughness which further adds to the improved mechanical interlocking. The woven basalt fabric of 380 g/m^2 having a density of 2630 kg/m^3 was used as the outer layer confinement. The fiber thickness varied from 0.8 to 1 mm.

2.2. FRP composite preparation

Epoxy resin and hardener were mixed in the proportion of 100:15 and MWCNT in weight percentages of 0.5, 1 and 1.5% were added into the epoxy binder (Tehrani et al., 2013). Using a 20 kHz frequency ultrasonic probe sonicator, MWCNT was evenly dispersed in the epoxy resin, the mixing period being 30 minutes. The MWCNT-epoxy mixture is then used to prepare epoxy composites by conventional hand layup method for assessing the various properties. The curing of the composites was carried out at room temperature for 72 hours and subjected to the evaluation of various properties (Sarath Kumar et al., 2021).

2.3. Specimen preparation and nomenclature

Wet layup technique was followed for the process of FRP wrapping around the concrete specimens and the MWCNT incorporated epoxy resin was used as the matrix for the composite strengthening system. The dimensions of all the concrete specimens were fixed as 150 mm diameter and 300 mm height. Two different fiber systems were used in the study, mainly sisal fiber reinforced (SFRP) as internal and basalt fiber reinforced (BFRP) polymer as external confinement. Surface preparation of the specimens was carried prior to the FRP wrapping. During this phase lateral surfaces were cleaned and roughened to have proper adhesion of the FRP. The epoxy matrix consists of resin and hardener along with an adequate percentage of MWCNT, and was thoroughly mixed using ultrasonic probe sonicator for a period of 30 minutes just prior to the application. One layer of SFRP was then wrapped around the radial surface in the hoop direction providing lateral confinement. Special attention was taken to ensure proper bonding between the FRP layers and concrete surface and the air entrapped between the fiber sheets and concrete surface was removed using surface rollers. Similar technique was adopted for the subsequent layers and proper bonding between the layers was established (Fig. 1). Prior to testing and exposure to severe environmental conditions the confined specimens were cured at room temperature for 7 days (Ispir et al., 2018).

To understand the type of specimen, following nomenclature is adopted throughout the study. The first letter represents the specimen material (C denotes concrete, and E represents Epoxy). The first digit shows the weight percentage of CNT in the polymer matrix whereas the letter succeeding it denotes the presence of CNT in the polymer matrix (i.e., 1C). The next digit and the succeeding alphabet explain the number of sisal FRP layers (i.e., 2S) followed by the basalt FRP layers (i.e., 2B).

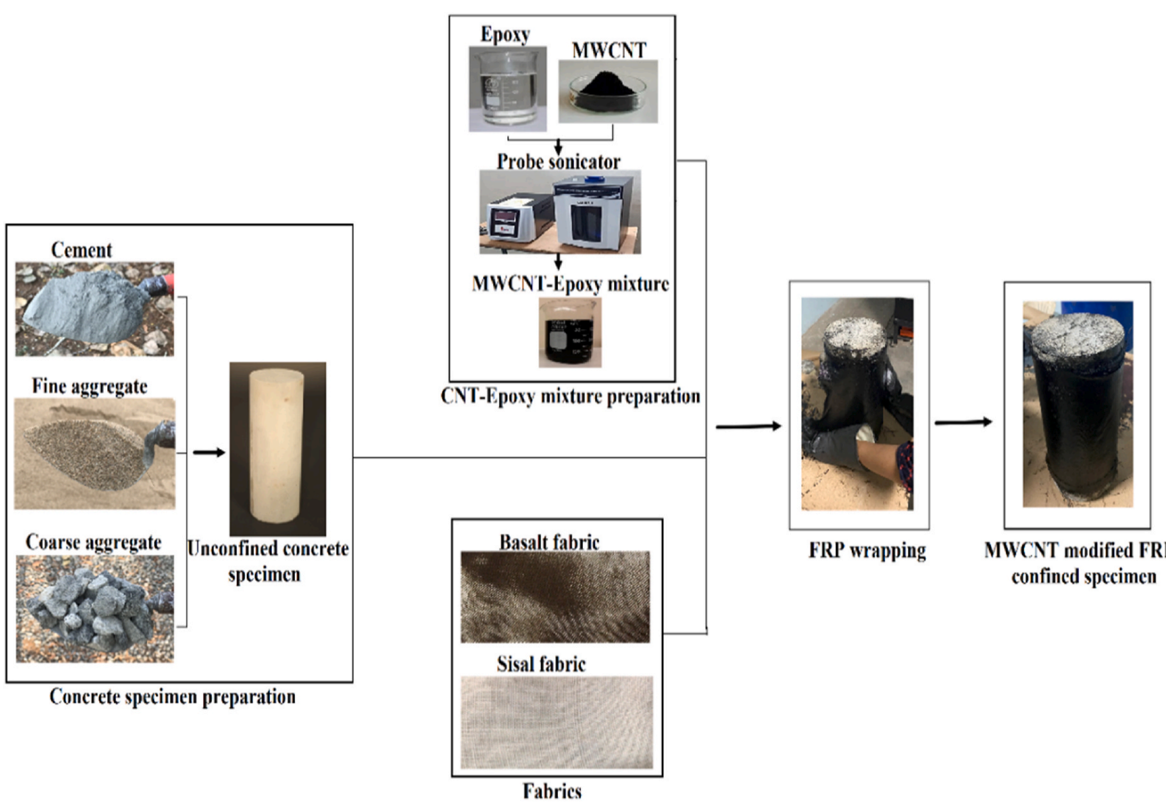


Fig. 1. Schematic representation of confined concrete specimen preparation.

C-E1C2S2B is an example of hybrid confined concrete specimen, prepared with two layers of sisal fiber sheet as inside layers and basalt fiber in 2 layers as outer jacketing of hybrid FRP specimen with 1 wt % of CNT in the epoxy matrix. E−1C2S2B specimen is an epoxy- CNT specimen prepared with two sisal FRP sheet and two basalt FRP sheets with 1 wt % of CNT in the matrix, which is used to assess the properties of fibers impregnated with MWCNT added epoxy composites.

Five categories of confined samples were considered in the investigation; such as SFRP specimens with and without MWCNT (cylinders confined with sisal FRP jackets), SBFRP hybrid specimens with and without MWCNT (cylinders confined by sisal and basalt FRP jackets), and control specimens (unconfined cylinders). These specimens were subjected to different environmental conditions separately, exposure to an elevated temperature of 300 °C, an acid environment for 120 days, an alkaline environment for 120 days and saltwater and normal water conditions for 120 days. In total 100 specimens were prepared and tested in this study.

2.4. Instrumentation and test procedure

To understand the effect of adverse environmental conditions on the confined concrete, the compressive strength of the samples exposed to the various exposure conditions was estimated using a uniaxial compression test (ASTM C39). All the specimens were subjected to displacement-controlled loading at the rate of 0.2 mm/min. Linear Variable Differential Transducers (LVDT) and strain gauges were employed to monitor the axial deformation and based on these the stress versus strain curves were plotted. An ultrasonic pulse velocity (UPV) test setup was used to study the propagation of cracks within the concrete core. The direct transmission method was adopted and the transducers were kept at the longitudinal ends of the specimens. The travel path was set to 0.3 m and time frame to 0.1 ms.

3. Results and discussion

3.1. Mechanical properties of epoxy composites

The tensile behaviour of the epoxy and its nanocomposites were studied as per ASTM D638 standard. An INSTRON 4502 Universal testing machine was utilized at 1 mm/min cross head speed. Epoxy samples with varying percentages of MWCNT and different layers of hybrid fiber systems were tested and the tensile properties obtained are reported in Table 2. From Table 2 it can be concluded that MWCNT incorporation enhanced the tensile properties significantly. The tensile strength exhibited by neat epoxy samples was 38 MPa along with an elongation at break of 7.8%. Further, studies revealed that in epoxy-fiber multiscale composites an increment in MWCNT content resulted in considerable improvement in tensile properties. The tensile strength enhanced more than 50% with 1 wt% of MWCNT addition to the epoxy and when multiscale composites were considered, a greater enhancement in tensile strength by more than 160% was observed for 1 wt % of MWCNT incorporated epoxy-hybrid fiber composites. The improvement in modulus and tensile strength could be credited to the enhanced load carrying capacity of MWCNT incorporated epoxy (Sarath Kumar et al., 2021). The large interfacial area between MWCNT and epoxy resin combined with uniform MWCNT dispersion contributes to the elevated mechanical properties in nanocomposites. After further increase in MWCNT content there is reduction in tensile properties for both epoxy and epoxy-fiber multiscale composites, which may be due to the agglomeration of the nano particles.

Table 2
Tensile properties of composites.

Sample	Tensile strength (MPa)	Young’s modulus (GPa)	Elongation (%)
E	38 ± 0.3	2.3 ± 0.03	7.8 ± 0.5
E−0.5C	45 ± 0.6	2.5 ± 0.02	9.0 ± 0.3
E−1C	62 ± 0.8	3.8 ± 0.04	10.7 ± 0.2
E−1.5C	49 ± 0.3	2.7 ± 0.01	8.9 ± 0.6
E−0C2S	70 ± 1.7	3.4 ± 0.6	10.7 ± 0.7
E−0C2S2B	74 ± 1.2	3.4 ± 0.8	11.2 ± 0.6
E−1C2S	85 ± 1.6	3.7 ± 0.7	12.0 ± 0.8
E−1C2S2B	100 ± 1.8	3.6 ± 0.8	10.8 ± 0.7

Transmission electron microscopy (TEM) analysis is conducted to analyse morphology of the developed composite along with the alignment of the fillers at the nano level (Rasana and Jayanarayanan, 2019). Fig. 2 presents the TEM images of E−0.5C, E−1C and E−1.5C epoxy-MWCNT composites. Nanoscale dispersion of MWCNT in the epoxy matrix is revealed in the TEM images. Fig. 2b explains the structure of nanocomposites consisting of 1 wt% MWCNT. It is evident that even after ultrasonication, MWCNT fillers have taken their tubular shape and are very well scattered all over the epoxy in E−1C. The entanglement of epoxy with MWCNT may assist in better load transfer and thus prevent crack propagation (Tehrani et al., 2013). Hence the optimum content of MWCNT for epoxy modification was considered to be 1 wt%. Nanoparticles those were not divided even after the ultrasonication could be observed in the form of clusters at some locations for 1.5 wt% (Fig. 2c), which results in the reduction in interfacial area of MWCNT and epoxy. This further reduces the bonding between MWCNT and epoxy. Thus, addition of MWCNT improves the mechanical properties of the resulting nanocomposite. However, when the nanofiller content increases, the agglomeration and aggregation produce clusters forming stress riser points and impact the mechanical properties negatively. In this case, the finest MWCNT content was observed as 1 wt% where the tensile strength was highest.

3.2. Compressive behavior of cylinders

Table 3 presents the compression test results of confined and unconfined concrete specimens. Clearly, the FRP confined cylinders experienced a substantial increment in terms of ultimate strength and ductile property. Here the failure is mainly because of FRP rupture. SFRP wrapped specimens exhibited a catastrophic failure in an abrupt way. Crack initiation in the form of clicking sounds were initiated followed by an explosive sound signifying FRP rupture. This sort of rupture failure was mainly observed at locations near mid-height and overlap zones along with crushing of concrete core. However, an unlikely failure pattern was observed for MWCNT incorporated HSBFRP confined specimens, where the failure was gradual with a combination of breaking of FRP layers. The confinement effect attributed by the incorporation of MWCNT with FRP wrapping was considered as a major reason for the enhanced load carrying capacity. When these specimens are considered, the inner FRP layers (SFRP) ruptures earlier without causing much damage which is visible from outside, after which the external FRP layers (BFRP) ruptures on further loading around the mid region of specimens. Similar failure patterns were reported by Ispir M (Ispir, 2015).

The confinement effectiveness is shown as f'_{cc}/f'_{co}, where f'_{co} signify the unconfined strength and f'_{cc} represents the confined concrete strength. As reported in Table 3, the C-E1C2S2B specimen recorded a compressive strength of 27.31 MPa, indicating an increase of 91% relative to that of the unconfined specimens. Moreover, the C-E0C2S specimen recorded minimum strength of 16.91 MPa, indicating an increase of 18% relative to that measured in the reference. The axial stress-strain curves for the confined and unconfined specimens are demonstrated in Fig. 3. In all the cases of FRP confined specimens, three different zones can be observed (Benzaid and Mesbah, 2010). The initial linear region mainly governs the stiffness of the concrete core as an indication that no confinement effect is activated by the FRP layers, and the concrete can carry the entire load. In the next zone, a non-linear transition is observed as the concrete tends to expand as it loses its stiffness and a confining pressure starts developing in the FRP layers. At this stage, the applied load overcomes the load carrying capacity of the

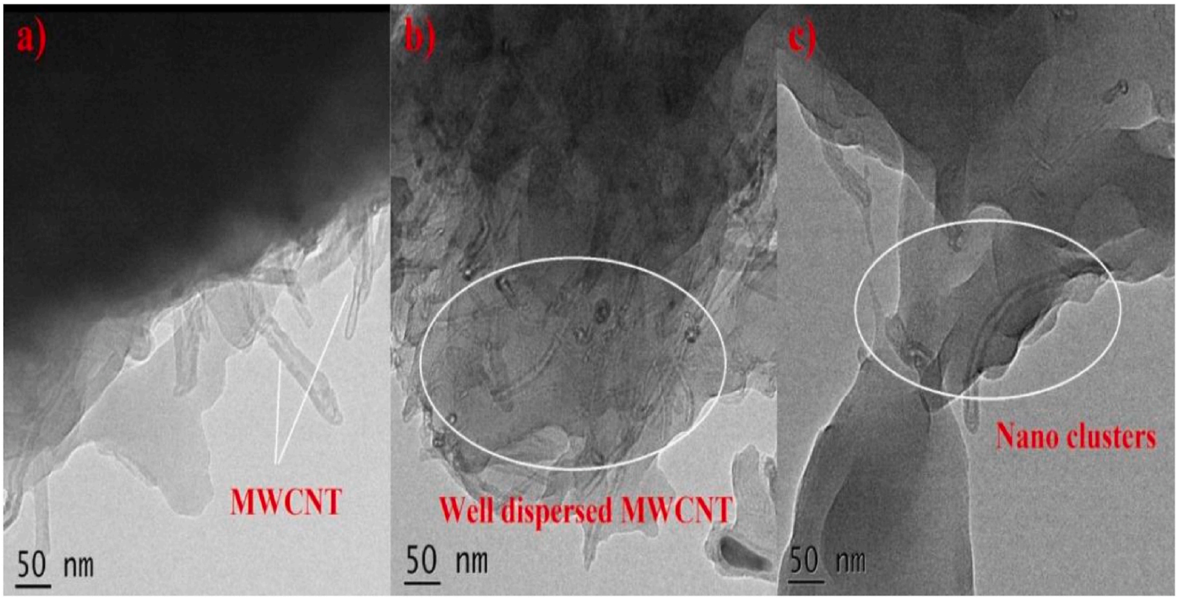


Fig. 2. Transmission Electron Microscope images of MWCNT modified Epoxy.

Table 3
Compression test results of specimens.

Sl No	Specimen	Axial compressive strength (MPa) (f'_{cc} or f'_{co})	Strength enhancement %	Confinement effectiveness f'_{cc}/f'_{co}	Energy absorbed (MPa)	Energy ductility index
1	CS	14.2 ± 0.6	–		6.37	1
2	C-E0C2S	16.9 ± 0.3	18	1.182	12.86	2.01
3	C-E0C2S2B	21.8 ± 0.2	45	1.454	22.60	3.54
4	C-E1C2S	20.8 ± 0.5	45	1.454	23.02	3.61
5	C-E1C2S2B	27.3 ± 0.8	91	1.908	34.50	5.41

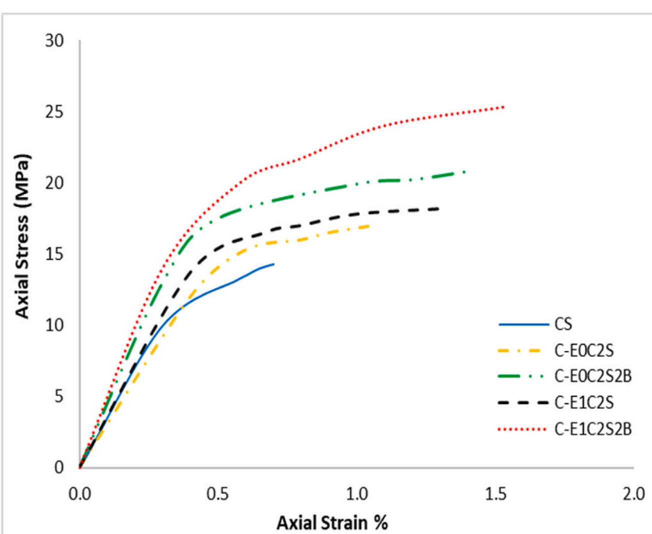


Fig. 3. Axial stress-strain curves of unconfined and confined specimens.

concrete core. Finally, in the last stage the concrete core cracks completely and FRP confinement is fully activated providing an additional load carrying capacity/lateral protection to the concrete core and thereby avoids catastrophic failure. At this stage the stiffness of the specimens is governed by the modulus of elasticity of FRP wraps. The stress strain curve is found to increase linearly until the failure of FRP layers. Both compressive strength and ultimate strain are significantly enhanced at this point.

Apart from improving the compressive strength, HSBFRP contributes to the enhancement of energy absorption and ductility of confined specimens. To avoid catastrophic failure, the structures are recommended to undergo a certain amount of deformation and ductility is the measure of deformation capacity of structure. Here, the ductility parameter is analyzed as the energy ductility index of the specimens which is taken as the ratio of energy absorption of confined specimens to that of unconfined specimens (Padanattil et al., 2017). The specimens exhibiting ductile behavior tend to show proper warning before failure due to their greater energy absorption rate. It could be noticed from Table 3 that FRP confinement marked a highest ductility index of 5.41 particularly by HSBFRP specimens. Also, the energy absorption is profoundly dependent on the type of FRP system used. The energy absorbed by MWCNT incorporated FRP confined specimens is 34.5 MPa which is almost six times more than the energy absorbed by unconfined specimens. Hence, the enhancement differs with the percentage of MWCNT, number of FRP layers and type of FRP (Ali Dadvar et al., 2020).

3.3. Durability analysis

Durability is defined as the ability of the materials to withstand weathering actions, chemical attack, and abrasion without compromising its desired engineering properties. Based on the actual adverse environmental conditions the concrete structures may undergo, four different cases are considered in the present study. This includes an elevated temperature of 300 °C, exposure to an acid, alkaline, water and sea water conditions for 120 days. A total of 6 unconfined specimens, 12 specimens wrapped with two layers of SFRP sheets, and 12 specimens wrapped with two layers each of hybrid sisal and basalt FRP sheets, with and without MWCNT incorporated epoxy as matrix were considered in all these studies.

3.3.1. Effect of elevated temperature

To examine the effect of temperature on the FRP wrapping, the cylinders were exposed to an elevated temperature of 300 °C for a period of 2 hours. At 300 °C, the concrete loses about 20% of its initial strength (Kodur, 2014). After 2 hours of exposure, the specimens were allowed to cool down to room temperature and the strength was tested as per ASTM C39. The results were equated with the corresponding values at room temperature.

3.3.1.1. Axial compressive behavior and failure mode. From the axial compressive strength test results, it was observed that specimens subjected to 300 °C showed certain damages on the FRP surface due to the deterioration of epoxy. However, the MWCNT incorporated HSBFRP wrapped specimens showed better resistance at this temperature. From Fig. 4 and Table 4 it is evident that an appreciable reduction in the strength is observed with the exposure temperature, nevertheless, the values are higher compared to the unconfined control specimens.

The failure of unconfined specimens was consistent with a combination of crushing and splitting of concrete at high temperature, along with cracks and spalling of concrete on the surface. At room temperature the failure of confined specimens was gradual, while with exposure to elevated temperature the failure was rapid and explosive in nature, which may be due to the deterioration of FRP layers at high temperature (Al-Salloum et al., 2011). The resistance offered by the HSBFRP system was superior when compared with SFRP specimens at 300 °C. Furthermore, at high temperature, for MWCNT incorporated epoxy based specimens, the loss in compressive strength is less significant as evidenced from the recorded value of 24.036 MPa. Even after the exposure to elevated temperature, the specimen C-E1C2S2B300 exhibited more than a 60% enhancement in compressive strength compared with unconfined and unexposed specimens. This shows that MWCNT incorporation and hybrid fiber system has a significant influence on the resistance of jacketed specimens to high temperature.

3.3.1.2. Stress strain response and ductile behavior. Fig. 5 shows the stress–strain graphs plotted for the MWCNT modified FRP confined and unconfined cylinders exposed at 300 °C. From the plots it is observed that temperature rise does not have a significant impact on the stress strain pattern. It was confirmed that the passive nature of FRP confinement does not affect the slope of the first linear region, which is

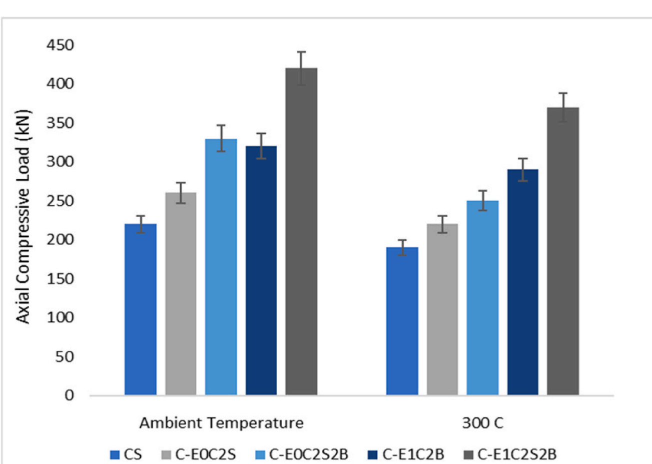


Fig. 4. Maximum compressive load of specimens when exposed to high temperature.

governed by properties of concrete core. The confining pressure generated by the FRP layer is activated in the region close to the peak strength of unwrapped concrete. HSBFRP wrapping manifested a higher increase in terms of axial strain. The highest strain values were exhibited by the MWCNT incorporated hybrid systems at elevated temperature when compared with SFRP confined specimens, which may be due to the softening of FRP layers or reduced confinement pressure offered by concrete core at elevated temperature. C-E1C2S2B300 specimens exhibited a maximum confinement ratio of 1.95 and axial strain value of 1.78 even after the exposure to elevated temperature. The ductility index and energy absorption exhibited by specimens are given in Table 4. Along with an increase in compressive strength, HSBFRP confinement could enhance the energy absorption and ductility. The energy absorbed by SFRP and HSBFRP wrapped specimens was 3.23 and 8.19 times the energy absorbed than the plain concrete after exposure to 300 °C. It could be observed from Table 4 that the percentage incorporation of MWCNT and type of FRP confinement directly influence the energy absorption nature of confined specimens.

3.3.2. Effects of chemical attack

Three sets of 30 specimens were exposed to acidic and alkaline chemical environments for a period of 120 days. The specimen nomenclature is taken as AC for acidic condition and AL for alkaline condition. Both confined and unconfined specimens were soaked in 5% sulphuric acid to create an acidic environment and 7% NaOH solution to create an alkaline environment for a period of four months. Three sets of samples were taken for the study including unconfined, SFRP confined and HSBFRP confined specimens.

3.3.2.1. Compressive strength and failure modes of specimens. Based on the visual inspection of the specimens subjected to chemical attack for a period of 120 days, it was observed that the unconfined specimens were immensely affected as evidenced from the spalling and cracking of concrete as shown in Fig. 6. On the contrary, confined specimens remained in their initial condition without any visible damages to the concrete core. FRP confinement showed a significant resistance to chemical attack under both acidic and alkaline environments (Mohammedameen et al., 2019). SFRP layers at the outer surface were partially influenced by the chemical environment and the inner sides were observed to be unaffected.

Upon the application of compression loading on wrapped specimens, minor cracks were developed over the FRP and the concrete core crumpled post the rupture of FRP layers (Zhou et al., 2016). In the case of MWCNT incorporated hybrid FRP specimens the overlapping zones were held intact and no delamination was detected. During loading, the crack formation was initiated around the end regions of the cylinder due to high-stress concentrations and the cracks progressed towards the middle region until failure. For all the confined specimens the failure was observed predominantly at the middle region of cylinders. Fig. 7 displays the failure pattern of control specimen and C-E1C2S2B-AC tested after 120 days of chemical exposure. From the failure patterns and test results, it was noticed that the exposure conditions and time period considerably affect the failure mode of the unconfined specimens while exposure period and conditions does not have much influence on the failure mode of the confined specimens. From Table 5, the compressive strength of the MWCNT incorporated FRP wrapped specimens were 24.6 MPa and 26.6 MPa, whereas for unconfined specimens reported a value of 9.7 MPa and 11.6 MPa under acidic and alkaline environments respectively. Hence the performance of MWCNT incorporated HSBFRP wrapped samples was commendable with a greater resistance towards these harsh environments compared to unconfined specimens as noticed in Fig. 8.

3.3.2.2. Stress strain and ductile behavior. The ultimate strain recorded in the case of confined specimens was increased compared with that of

Table 4
Compression test results of specimens when exposed to elevated temperature.

Sl No	Specimen	Axial compressive strength (MPa) (f'_{cc} or f'_{co})		Confinement effectiveness f'_{cc}/f'_{co}		Energy absorbed (MPa)		Energy ductility index	
		Ambient Temp	300 °C	Ambient Temp	300 °C	Ambient Temp	300 °C	Ambient Temp	300 °C
1	CS	14.2 ± 0.6	12.3 ± 0.3	–	–	4.416	3.761	1.00	0.85
2	C-E0C2S	16.9 ± 0.3	14.2 ± 0.4	1.18	1.01	12.679	12.140	2.87	3.23
3	C-E0C2S2B	21.8 ± 0.2	16.2 ± 0.2	1.45	1.14	22.399	20.291	5.07	5.40
4	C-E1C2S	20.8 ± 0.5	18.8 ± 0.7	1.44	1.32	23.959	23.421	5.43	6.23
6	C-E1C2S2B	27.3 ± 0.8	24.3 ± 0.5	1.91	1.68	34.464	30.802	7.80	8.19

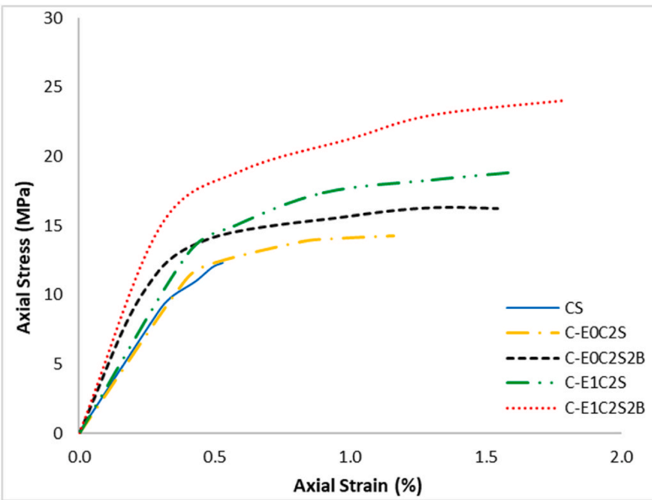


Fig. 5. Axial stress-strain curves when exposed to elevated temperature of 300 °C.

unconfined specimens in both acid and alkaline environments. A considerable reduction in the compressive strain of unconfined specimens namely CS-AC and CS-AL was witnessed. The specimens C-E1C2S2B-AC and C-E1C2S2B-AL were unaffected on exposure to severe environmental conditions. Therefore, it can be concluded that the MWCNT incorporated hybrid FRP confinement could efficiently withstand the deformability of the specimens even at severe environmental conditions compared to unconfined ones. Fig. 9 demonstrates the stress-strain curve including axial stress and axial strain of the unconfined and confined specimens subjected to chemical exposure. From the graph it could be derived that the ductility of SFRP cylinders reduced on exposure to acidic and alkaline environments unlike the hybrid confined specimens. From Table 5 an enormous decrement was detected in the energy absorption and ductility index of unconfined specimens after the exposure. MWCNT modified HSBFRPs exhibited an energy absorption of 6.24 and 7.47 times that of unwrapped samples when exposed to acid and alkaline environments.

3.3.3. *Effects of sea water exposure*

Sea water/marine environment was created by mixing 3.5% NaCl solution per liter of water. FRP wrapped specimens conditioned in room temperature were immersed in the NaCl solution for a total of 120 days. The specimen nomenclature is taken as SW for sea water condition and WA for normal water condition.

3.3.3.1. Compressive strength and stress strain behavior. After the visual inspection of specimens exposed to a period of 120 days, it was revealed that all the specimens remained in their original state and no traces of cracking and spalling were detected. Seawater is not considered as a hazardous environment for plain concrete and does not influence the ultimate load carrying capacity as observed in Fig. 10. However, sea water environments can be dangerous to reinforced cement concrete (RCC) components due to the corrosion of steel reinforcement due to salt water penetration through the cracked surface and in such cases hybrid FRP may be recommended. In Table 6, the residual mechanical properties are shown in comparison to the control specimens. It can be observed that HSBFRP wrapped systems exposed to seawater and potable water environments showed a similar ultimate capacity. C-E1C2S2B, C-E1C2S2B-SW and C-E1C2S2B-WA specimens exhibited an axial compressive strength of 27.31 MPa, 26.959 MPa and 26.959 MPa respectively with almost 90% enhancement in compressive strength when compared to unconfined specimen. This may be credited to the

Fig. 6. Specimens after acid environment exposure.

Fig. 7. Failure pattern of specimens exposed to acid attack (a) unconfined cylinder (b) C-E1C2S2B-AC.

Table 5
Compression test results of specimens after exposure to chemical attack.

Sl No	Specimen	Axial Compressive strength (MPa) (f'_{cc} or f'_{co})		Confinement effectiveness f'_{cc}/f'_{co}		Energy absorbed (MPa)		Energy ductility index	
		Acidic	Alkaline	Acidic	Alkaline	Acidic	Alkaline	Acidic	Alkaline
1	Unexposed- CS	14.2 ± 0.6		–		4.416		1.00	
2	Exposed- CS	9.7 ± 0.3	11.6 ± 0.5	–	–	3.437	4.159	0.78	0.94
3	C-E0C2S	13.6 ± 0.2	14.9 ± 0.8	0.955	1.045	10.822	11.664	2.45	2.64
4	C-E0C2S2B	17.5 ± 0.5	19.4 ± 0.2	1.227	1.364	19.227	20.827	4.35	4.72
6	C-E1C2S	18.1 ± 0.7	19.8 ± 0.8	1.273	1.386	20.845	24.434	4.72	5.53
7	C-E1C2S2B	24.6 ± 0.4	26.6 ± 0.5	1.727	1.864	27.554	32.966	6.24	7.47

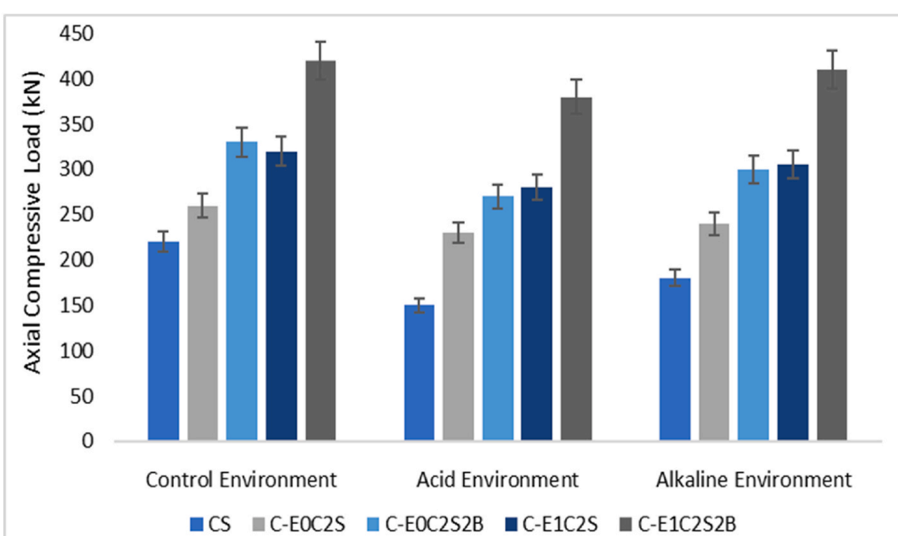
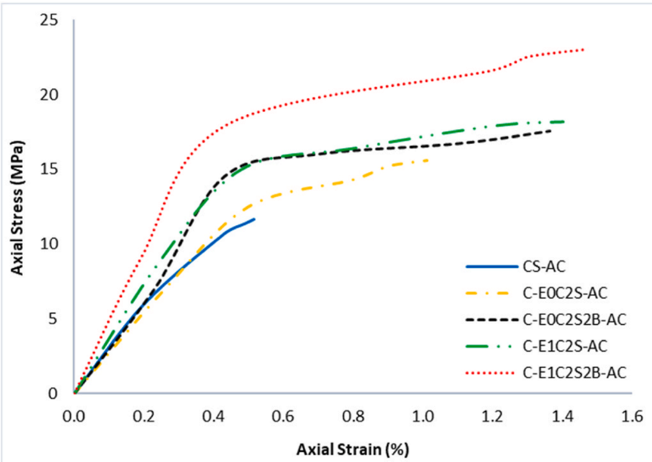


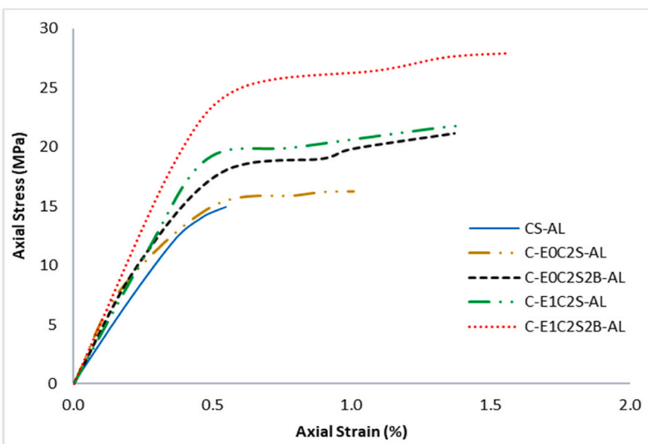
Fig. 8. Maximum compressive load of specimens on exposure to chemical conditions.

collective effect of MWCNT modification and hybrid fiber system resisting environmental water aging conditions. The unconfined specimens exhibited a compressive strength of 14.291 MPa and upon exposure to sea water and water environments, the compressive strength was reduced by 30%. Also, the immersion in salt bath exposes the fiber to a saline chemical attack which reduces its ultimate tensile strength (Toutanji and Deng, 2002).

Fig. 11 shows the stress-strain curves of columns with the different FRP confinement under water and sea water environment. From the results it is clear that FRP confined specimens exhibited better resistance to marine and water environments when compared with unconfined specimens. Among the FRPs, MWCNT incorporated HSBFRP confined



(a)



(b)

Fig. 9. Axial stress-strain curves of specimens exposed to chemical attack a) Acidic Condition b) Alkaline Condition.

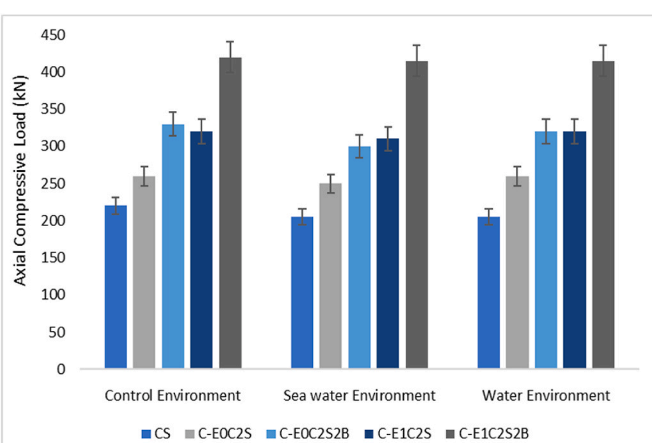


Fig. 10. Maximum compressive load of specimens upon exposure to Sea water conditions.

specimens remain almost unaffected under these environments exhibiting better mechanical performance. The confinement effectiveness for MWCNT incorporated hybrid SBFRP is 1.886 for marine as well as water environments when compared to unconfined concrete. Both the matrix type and fiber system played a significant part in the improvement of ultimate strength. A significant reduction in terms of ductility was observed for unconfined and SFRP confined specimens exposed to the mentioned conditioning regimens especially after saline immersion. It can be explained with a damage mechanism activated by salt ions in the wrapping systems, allowing moisture penetration.

3.3.3.2. Ductile behavior and energy absorption. Along with the improvement in mechanical properties and durability, FRP confinement is also capable of improving the ductility of specimens (Yan, 2016). The seawater and water exposed specimens exhibited comparable ductility and energy absorption behavior due to the superior performance of MWCNT incorporation and hybrid FRP system. Hybrid FRP confined columns performed better than the sisal FRP ones, whereas the unconfined specimens exhibited an inferior performance. The energy absorbed by C-E1C2S2B-SW, and C-E1C2S2B-WA was 6.52 and 6.7 times that of unconfined concrete as seen in Table 6. In general, MWCNT modified HSBFRP confined specimens possess a higher toughness and ductile nature due to their strain hardening nature particularly after initial rupture of FRP wraps. Also, when hybrid confinements are considered, C-E1C2S2B-SW and C-E1C2S2B-WA specimens yielded a greater lateral displacement ability. Hence, MWCNT modified hybrid FRP confinements can be considered as structural members which demand high strength and ductility.

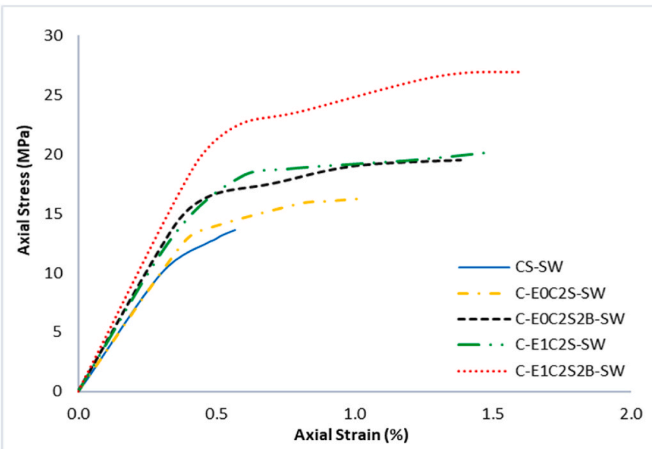
3.4. Ultrasonic pulse velocity (UPV) test

Apart from analysing the strength and energy absorption characteristics of all these specimens, UPV test is carried out to understand the confinement effect of modified epoxy and hybrid FRP on the inner core. UPV test is a non-destructive testing (NDT) adopted to understand the concrete quality by measuring the velocity or time of ultrasonic pulses while travelling between transmitter to receiver. The testing procedure was as per IS: 13311-1 (1992). The wave propagation was initiated and the pulse travels through the concrete and is received by a similar transducer on the opposite surface. The pulse velocity and travel time was then obtained. The UPV values corresponding to specimens exposed to the varied environmental conditions and subjected to compressive load are shown in Fig. 12. The unconfined specimens exhibited, a sudden decrease in velocity showing that large number of inner cracks or widening of cracks occurred at a fast pace when exposed to harsh environment implying concrete core failure internally. While when confined specimens are considered the variation in velocity was gradual. Therefore, it can be concluded that as the amount of wrap reduces the intensity of crack formation to minimal. Under acid exposure the maximum reduction in pulse velocity was exhibited by unconfined specimens followed by SFRP confined specimens and greatest pulse velocity was exhibited by HSBFRP confined specimens. Reduction in pulse velocity directly depends on the number and intensity of internal cracks as well as the width of cracks developed. It can be derived that the confinement provides an internal resistance to the concrete core from failure and the MWCNT incorporation enhances the efficiency of confinement.

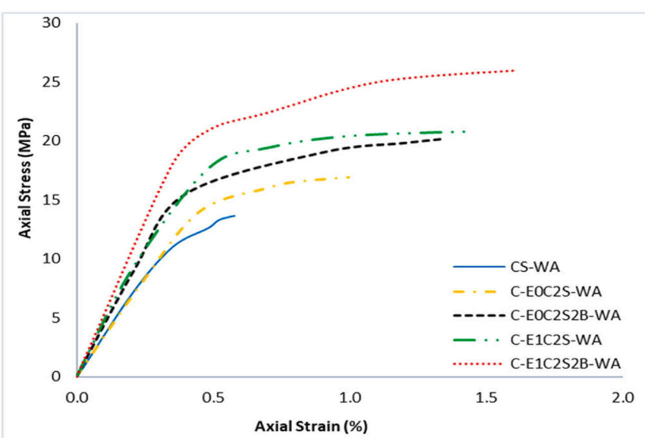
The enhanced load bearing capacity offered by the newly developed FRP confinements could be credited to the presence of the MWCNT incorporated epoxy. Epoxy manifests brittle nature and upon loading, it tends to crack. With MWCNT incorporation mechanical interlocking with epoxy chains is formed, and upon further loading a bridging effect will be created, which helps in the stress transfer from low modulus epoxy to higher modulus MWCNTs. During the process of loading, cracks are developed within the concrete core and on further loading the cracks will be transferred to the FRP layers. The existence of MWCNT deflects and bridges the micro cracks as seen in Fig. 13 when compared to neat epoxy confined specimens.

Table 6
Compression test results of specimens when exposed to Sea water and water environment.

Sl No	Specimen	Axial Compressive strength (MPa) (f'$_{cc}$ or f'$_{co}$)		Confinement effectiveness f'$_{cc}$/f'$_{co}$		Energy absorbed (MPa)		Energy ductility index	
		Sea water	Water	Sea water	Water	Sea water	Water	Sea water	Water
1	Unexposed- CS	14.2 ± 0.6		–		4.416		1.00	
2	Exposed- CS	13.2 ± 0.3	13.3 ± 0.1	–	–	4.117	4.429	0.93	1.00
3	C-E0C2S	16.2 ± 0.6	16.5 ± 0.4	1.136	1.159	10.950	10.524	2.48	2.38
4	C-E0C2S2B	20.9 ± 0.2	21.1 ± 0.3	1.464	1.477	18.894	18.810	4.28	4.26
6	C-E1C2S	20.1 ± 0.5	20.5 ± 0.5	1.409	1.436	21.852	21.472	4.95	4.86
7	C-E1C2S2B	26.9 ± 0.4	26.9 ± 0.9	1.886	1.886	28.778	29.59	6.52	6.70



(a)



(b)

Fig. 11. Axial stress-strain curves of specimens exposed to a) Sea water Condition b) Water Condition.

4. Statistical evaluation of test results

A GLM-ANOVA was executed at a significant level of 0.05 to assess the performance of the MWCNT incorporated FRP confined specimens exposed to various environmental conditions. Tables 7 and 8 provide the results of the statistical confirmation of the chosen model using analysis of variance (ANOVA) for compressive strength.

The significance of the parameters impacting compressive strength (percentage weight of MWCNT, number of sisal layers, number of basalt layers and exposure conditions) was determined by performing ANOVA General Linear Model using Minitab software. Individual factors such as percentage weight of MWCNT and the number of basalt layers were identified as significant variables on the basis of p-value being less than 0.05. The number of sisal layers was designated as non-significant as the p-value was greater than 0.05, and is kept constant as two layers throughout the study. Since the influence of sisal layers is subtle when compared to other parameters, the utilization of sisal layers is ineffectual with respect to compressive strength. Also, the specimens were exposed to various exposure conditions (elevated temperature, acid, alkaline, salt water and water) and compressive strength of these specimens was compared with the specimens that were exposed to normal environment. The compressive strengths of specimens exposed to normal and sea water environments did not differ significantly. Alkaline environment exhibited a moderate influence, whereas, the difference between the compressive strengths of the specimens which were exposed to normal conditions and acid and elevated temperature was significant.

4.1. Main effects plot

With the use of a main effects plot, the effects of specimen type and exposure conditions are presented. For this purpose, various types of specimens were subjected to different exposure conditions and their compressive strength was determined. From Fig. 14 it is clear that, the mean compressive strength of all the four types of specimens surpassed the mean value of the control specimen, which as a result, can be concluded that the specimens with fibers have better implementation results. 'Type of specimen' is the parameter which is showing more effect since the magnitude of mean compressive strength is higher than that of the other parameters which are 'Exposure condition' and 'Exposure temperature'. Exclusively, in the type of specimen, the specimen with 1 percentage weight of MWCNT, 2 sisal layers and 2 basalt layers have shown beneficial results. Concerning the second parameter which is exposure condition", the mean compressive strength attained during normal exposure condition has better magnitude than the other exposure conditions. Besides this, there is substantial difference among the mean compressive strengths of acid, alkaline and elevated temperature conditions. Nevertheless, the gap among the magnitudes of mean compressive strength in normal water and salt water exposure conditions are not significant. Hence based on Fig. 14 it can be inferred that within all the environmental conditions considered MWCNT incorporated hybrid SBFRP specimens are highly recommended compared to other specimens. Also, they exhibit better performance under alkaline, marine and water environments along with the normal condition.

The economic feasibility of the application of MWCNT incorporated epoxy as matrix in FRP confinement system is assessed based on the cost comparison presented in Table 9. The additional cost incurred for MWCNT incorporation in epoxy can very well be justified by the percentage improvement in the load bearing capacity achieved for the confined specimens. While there was 46% enhancement in axial compressive strength for neat epoxy based FRP confined columns, MWCNT incorporated epoxy based confinements manifested 91% improvement, when compared to unconfined specimens.

5. Conclusions

Based on the study conducted to assess the strength and durability performance of the FRP confined and unconfined concrete specimens

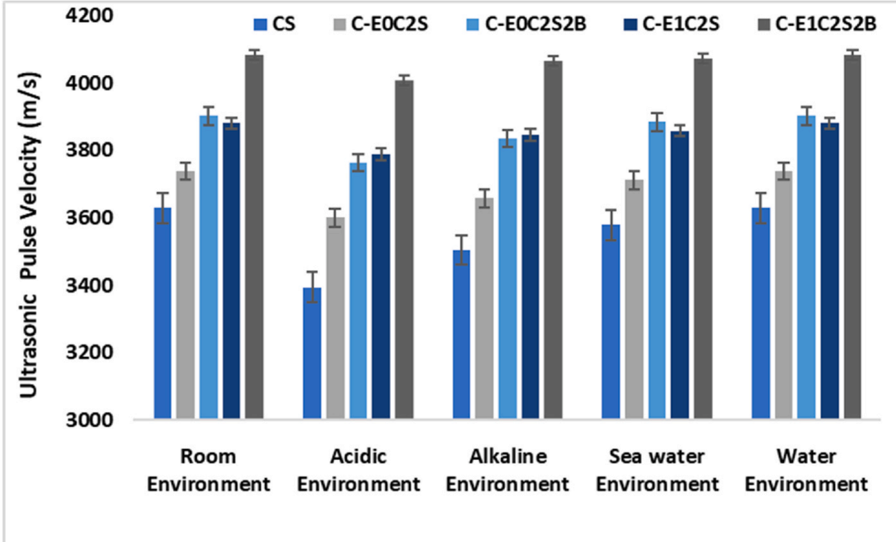


Fig. 12. Pulse velocity response of specimens for different environmental conditions.

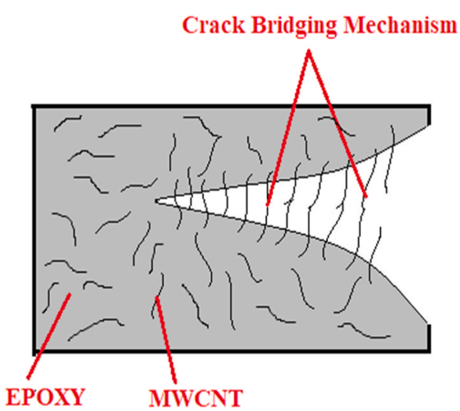


Fig. 13. Crack bridging by MWCNT in epoxy.

Table 7
Statistical evaluation of the test results.

Variables	Adj Sum of Squares	Adj Mean Square	F-Value	P-Value	Significance
Percentage weight of MWCNT	42869	42869.0	97.21	0.00	Yes
Number of sisal layers	1652	1651.9	3.75	0.07	Constant
Number of basalt layers	40038	40038.4	90.79	0.00	Yes

Table 8
Analysis of variance for exposure condition.

Exposure condition	Adj Sum of Squares	Adj Mean Square	F-Value	P-Value	Significance
Acid	5760	5760	42.67	0.00	Yes
Alkaline	1322.5	1322.5	18.24	0.01	Moderate
Sea Water	490	490	10.59	0.03	No
Water	90	90	4.24	0.109	No
Elevated temperature	5290	5290	24.6	0.00	Yes

with and without MWCNT incorporation in epoxy, the following conclusions were arrived at.

- When nano and multiscale composites are compared, the optimal MWCNT content was derived to be 1 wt % with maximum enhancement in mechanical properties by 160%.
- Axial load bearing capacity of compression members in structures could be considerably enhanced by MWCNT incorporated epoxy based FRP confinement along with noticeable enhancement in ductility and energy absorption characteristics.
- All the confined specimens showed higher compressive strengths when compared with unconfined samples in a range of 25%–45% for SFRP and 75%–90% for HSBFRP wraps, while the unconfined specimens exhibited poor performances under exposure to various environmental conditions listed.
- The MWCNT modified HSBFRP confined specimens exhibited an energy absorption of 6.24 times that of unconfined specimens upon chemical exposure while the unconfined exposed specimens exhibited declined ductility index by 0.94 as evidence of the enhanced energy absorption and ductility index of FRP confined specimens with nano modification of epoxy.
- In the case of MWCNT incorporated hybrid SBFRP confined columns the strength and nature of the specimens remained unaffected with a strength reduction less than 5% after being exposed to sea water and water environments. Hence, it can be used as a retrofitting material under marine environment.
- Statistical analysis also specified that MWCNT incorporated HSBFRP specimens exhibited superior performance than epoxy confined specimens and the dominant factor that governs the performance of HSBFRP confined specimens were the FRP confinement and MWCNT incorporation.

Hence it can be concluded that the strengthening/retrofitting of concrete columns can be carried out with the natural/organic fibers, and thus can completely eliminate the use of artificial fibers which poses threat to the environment after their life period. The incorporation of MWCNT in epoxy for FRP confinement is proved as a promising technique to enhance the strength, energy absorption, ductility and durability of existing concrete structures compared to conventional epoxy based FRP confinement techniques. Overall, HSBFRP confinement can be considered as a worthy choice as a rehabilitation material for the concrete columns.

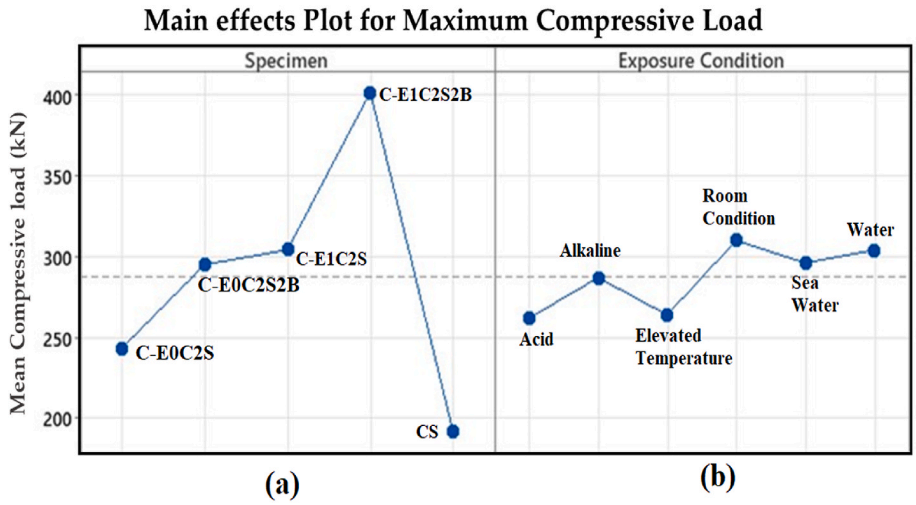


Fig. 14. Main effect plot for compressive strength in terms of (a) Specimen Type (b) Exposure Condition.

Table 9
Cost analysis of neat epoxy and MWCNT modified epoxy.

Neat Epoxy	MWCNT incorporated epoxy
Cost of epoxy per kg- INR 550	Cost of epoxy per kg- INR 550 Cost of 1 wt% (i.e., 10g of MWCNT in 1 kg of epoxy) - INR 640
Total = INR 550/-	**Total=INR 1210/-**
Enhancement in compressive strength of confined specimens with pure epoxy is 46%	Enhancement in compressive strength of confined specimens with MWCNT incorporated epoxy is 91%

* [1 US dollar = 82.1 Indian Rupees (INR)].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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