International Journal of Sustainable Built Environment (2015) 4, 248–264

HOSTED BY ELSEVIER

Gulf Organisation for Research and Development

International Journal of Sustainable Built Environment

ScienceDirect
www.sciencedirect.com

Original Article/Research

Confining concrete with sisal and jute FRP as alternatives for CFRP and GFRP

Tara Sen [a,*], Ashim Paul [b]

[a] Department of Civil Engineering, National Institute of Technology, Barjala, Jirania, Agartala 799046, Tripura (West), India
[b] Department of Civil Engineering, Royal Group of Institutions, Guwahati, Assam, India

Received 12 December 2014; accepted 21 April 2015

Abstract

This research paper presents an experimental investigation on the confinement strength and confinement modulus of concrete cylinders confined using different types of natural fibre composites and a comparative performance analysis with different artificial fibre based composite materials. The paper also highlights the need to switch over from the utilization of artificial fibres, which are non-renewable and fossil fuel products, to environmental beneficial materials like green fibres. The utilization of plant products like sisal and jute fibres and their composites in various structural engineering applications addresses the issues of sustainability and renewability with constructional materials. The paper describes a suitable mechanical treatment method like high temperature conditioning, which aids us in further improving the properties of these woven natural materials like sisal and jute for composite fabrication and utilization. Heat treated natural fibres of woven sisal and jute were utilized for confining concrete cylinders similar to CFRP and GFRP confinement and their confinement characteristics were obtained and compared. All the cylinders were subjected to monotonic axial compressive loads, so as to evaluate the effect of confinement on the axial load carrying capacity and all their failure modes were discussed thoroughly. The results indicated superior performance by sisal FRP as well as jute FRP confined cylinders as compared to controlled or unconfined cylinders, also sisal FRP wrapped cylinders displayed ultimate axial load of comparable magnitude to CFRP confinement. Natural FRP confinement displayed superior confinement modulus and confinement strength, also the ultimate axial load of concrete cylinders confined with natural FRPs underwent 66% enhancement by sisal FRP and 48% enhancement by jute FRP, in comparison with controlled or unconfined cylinders. Enhancement in axial load carrying capacity was 83% with CFRP confinement and 180% with GFRP confinement. Although natural FRP displayed lower enhancement in axial load carrying capacity in comparison with artificial FRP confinement, but enhanced load carrying capabilities alongside superior sustainability and environmental friendly indices could be obtained using the same, because of various advantages associated with the use of natural fibres.

Keywords: Jute FRP; Sisal FRP; CFRP; GFRP; Confinement

1. Introduction

A large number of studies have been undertaken world-wide to evaluate the behaviour of concrete confined by fibre reinforced polymeric materials (FRPs). FRPs

* Corresponding author. Tel.: +91 9436541206.
E-mail address: tarasen20@gmail.com (T. Sen).
Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2015.04.001

being one of the most preferred materials for structural components be it beams, columns or slabs, retrofitting or rehabilitation, they also greatly increase ductility and energy absorption capabilities in these building components. FRPs have displayed remarkable increase in strength and ductility, when bonded to reinforced concrete (RC) elements, providing confinement throughout. Huge quanta of experimental and analytical works are available via many research resources for analysing and evaluating the mechanical behaviour of FRP-confined concrete (Xiao and Wu, 2000; Pessiki et al., 2001; Xiao and Wu, 2001, 2006; Elsanadedy et al., 2012; Micelli and Modarelli, 2013; Vincent and Ozbakkaloglu, 2013). A large quantum of data are available for FRP confined concrete cylinders subjected to axial compressive loads, but also all these data give knowledge and information regarding artificial fibres such as carbon fibre (CFRP), glass fibre (GFRP) and aramid fibre (AFRP) confined concrete cylinders. There are very scarce and limited data and research available on natural fibre based composite confined concrete cylinders. With the world moving ahead for finding a suitable replacement of artificial fibres, natural fibre utilization for various structural applications should be ventured into as they have shown lot of promise. Taking into account the basic raw-materials utilized for the manufacturing of these artificial fibres, we get to know that the raw-materials utilized for manufacturing all these fibres are non-renewable deposits on the earth that had been formed by millions and millions of years ago by virtue of nature forces. Artificial fibres such as carbon or glass or aramid fibres are all artificially fabricated and manufactured from various fossil fuel sources. Carbon fibres are mainly manufactured from coal or petroleum pitches, which make them non-renewable and non-sustainable in nature. Textile or fabric grade glass fibres are basically made from silica (SiO_2) sand. SiO_2 is also the basic element in quartz, a naturally occurring rock. With fast depleting layers of sand from river beds, because of the constructional activities resulting in unprecedented sand mining, we have to ensure that such unprecedented sand mining is checked and avoided so that catastrophical geo-hazards can be prevented. Also considering other facts that these artificial fibres are not renewable, bio-degradable, their waste disposal causes major environmental pollution, their manufacturing itself causes harsh environmental conditions for the factory workers, these materials cause excessive wear and tear in the instruments which are used for their manufacturing, and production releases toxic gasses in the atmosphere and also harmful chemicals are released, their handling causes heath related problems especially dermatitis problems, and finally these are non-sustainable materials which although come with obvious superior mechanical properties, but at the cost of various environmental-sustainability issues. On the other hand, natural fibres, which are cellulosic fibres have good mechanical properties, particularly sisal and jute fibres have displayed potential mechanical properties (Munikenche Gowda et al., 1999; Gassan and Bledzki Andrzej, 1999; Li et al., 2000; Rong et al., 2001; Ray and Sarkar, 2001; Kim and Seo, 2006; Stocchi et al., 2007; Wang et al., 2008; Liu and Dai, 2007; Summerscales et al., 2010). These properties of natural fibres can be further improved upon by suitable treatment methods, particularly considering woven fibres in fabric forms, mechanical treatment in the form of heat treatment is very effective in improving the mechanical properties of natural woven fibres or natural fabrics of plant fibres, for composite fabrication (Barreto et al., 2011; John and Thomas, 2008; Janeza and Croatia, 2010; Kaewkuk et al., 2010; Kabir et al., 2011; Milanese et al., 2011; Campos et al., 2012; Fa, 2015; Textile, 2015). Cellulose, which awards mechanical properties to the natural fibre, is ordered in micro-fibrils enclosed by the other two main components: hemicellulose and lignin. Lignin is an aromatic biopolymer, an integral cell wall constituent of all vascular plants and hemicelluloses are a large group of polysaccharides found in the primary and secondary cell walls of the plants. These three mentioned components are responsible for the physical properties of the fibres. These natural fibres can be effectively used in the manufacture of fibre reinforced polymer composites because they possess attractive physical and mechanical properties (Milanese et al., 2012; Joshi et al., 2004; Sapuan et al., 2006; Sreekumar et al., 2009; Ratna Prasad and Mohana Rao, 2011; Milanese et al., 2011; Alamri and Low, 2012; Sawpan et al., 2011; Nardone et al., 2012; Venkateshwaran et al., 2012; Maria Ernestina et al., 2013). They impart the composite high specific stiffness and strength, a desirable fibre aspect ratio, and biodegradability. They are readily available from natural sources and more importantly they have a low cost per unit volume basis. It should also be mentioned that the hollow nature of vegetable fibres may impart acoustic insulation or damping properties to certain types of matrices. These natural fibres have a lot of important features such as low cost, low density, higher specific resistance, biological degradability, CO_2 neutrality, renewability, good mechanical properties, non-toxicity, lesser abrasive nature to the instruments used for their manufacturing and production and can be easily modified by chemical or mechanical treatment methods. All these parameters involved with the natural fibres make them biodegradable, renewable and sustainable green fibres available so that their potential can be trapped and utilized for not only as a constructional material, but also as one which enhances structural properties by not harming the environment (Monteiro et al., 2013; Bledzki and Gassan, 1999; Zhang et al., 2005; Mathur, 2006; Xu et al., 2008; Satyanarayana et al., 2009; Singh Rajesh et al., 2009; Summerscales et al., 2010; La Mantia and Morreale, 2011; Hota and Liang, 2011; Langford, 2011; Moldan et al., 2012; James and Richard, 2012; Begum and Islam, 2013; López-Lara et al., 2013; Cristaldi et al., 2015). Their utilization can aid us to boost rural economy and rural empowerment. The investigation of the performance of natural fibre in fabric or woven form based FRP-wrapping or prefabricated sheet jacketing of the same around RC cylinders and their comparative analysis with the commonly used FRP confinement materials, such as CFRP and GFRP confined RC cylinders, would be up for an interesting study. Their comparative performances should be well evaluated to understand the potential of natural fibre composite confinement over artificial ones, so as to substantially enhance the axial compressive strength and ductility of concrete cylinders due to lateral confinement of FRP, additionally the various durability issues associated with natural FRPs also have to be studied in order to attain their long term usage in constructional fields. External confinement of concrete, by FRP fabric composite bonding, enhances its strength and ductility. Various experiments and analysis that have been carried out, are proving enough, and have displayed enhanced ductility pertaining to FRP confined cylinders, which are analogous to concrete columns or FRP confined RC beams (Ahmeda and Vijayarangan, 2008; Oehlers et al., 2009, 2013; Wang and Belarbi, 2011; Issa et al., 2011; Hussein et al., 2012; Said and Elrakib, 2013; Gunes et al., 2013). Until recently the external confinement was mainly provided by either artificial fibre composites of carbon fibres (CFRP), glass fibres (GFRP) or aramid fibres (AFRP), which indeed have displayed huge enhancement in strength and ductility of the concrete cylinders by virtue of their confining action. Another added advantage of FRP confinement is that it enhances strength and ductility parameters, without any substantial increase in the cross sectional characteristics or weight of the concrete component. Now a days, with the development and research being diverted to finding bio based replacement for artificial carbon or glass fibres, the confinement capabilities of natural fabric composite bonded to concrete components is a field, yet to be worked and analysed upon. A clear understanding of the strength and ductility of natural fibre based FRP-confined concrete is necessary for evaluating their confinement and ductility characteristic parameters. This research paper carries out an experimental investigation on the confinement strength and confinement modulus parameters of concrete cylinders fully confined and 50% confined (carried out by strip wrapping) by natural fabrics of jute and sisal, and also by artificial fabrics of carbon and glass composite wrapped concrete cylinders subjected to axial compressive loads. The research paper also compares the effectiveness of the different types of fibre composite wrappings in enhancing the axial load and the confinement strength of the concrete cylinders.

2. Mechanical characterization of FRP composite

2.1. Materials

The sisal and jute fabrics were collected from Extra Weave Private Ltd, Cherthala, Kerala, India. MBrace® FRP fibre, of two types, that is MBrace Carbon fibre CF 230 g and MBrace Glass Fiber EU 900 glass fibre, both in fabrics were collected from BASF Construction Chemicals Chandivali, Andheri East, Mumbai, India, and were used in this work. Also all other chemicals used for the fabrication of the natural jute FRP composite for the mechanical characterizations, such as MBrace saturant, which consists of Part A Resin, and Part B hardener were obtained from BASF Construction Chemicals Chandivali, Andheri East, Mumbai, India. Table 1 presents the properties of the MBrace saturant as supplied by the manufacturer.

2.2. Heat treatment of natural fibres in woven or fabric forms

The mechanical treatment in the form of heat treatment was carried out in the following manner: sisal and jute fabric mats were cut into the size as required for flexural strength test as per ISO 14125:1998 and tensile strength test as per ISO 527-4, 1997(E) ISO 527-4, 1997, for the natural fibre woven mats. Fig. 1 clearly represents the heat treatment mechanism utilized for high temperature conditioning of the natural woven fibres of sisal and jute. These woven fibre mats were then placed into the oven at 50 °C for 48 h. After that the samples were kept in an air tight chamber so that atmospheric moisture could not be absorbed by these samples. Basically, when the fibres are exposed to atmosphere, it results in the absorption of moisture. This moisture which gets accumulated in the fibres requires to be eliminated, this elimination of the moisture from the fibres can be attained by the process of heat treatment. Heat treated composites of natural fabrics or mats have shown to display a higher strength than untreated composites of natural fibre fabrics or mats. The effect of elevated temperature conditioning can be described as a threefold effect on the cellulosic fibres of jute and sisal. Firstly the modification of cellulosic structure by enhanced cross-linking, then secondly, increased amount of crystallinity in the fibres, and thirdly, by de-moisturization, which improves adhesion between fibres and natural rubber backing. High temperature in general accelerates as well as activates chemical reactions. In cellulosic materials, such as natural fibres of jute and sisal, which consists of about 65–70% of cellulose, it leads to the formation of radicals, which in turn leads to several other reactions. Also, at elevated temperatures, there is cross-linking of cellulose, which reduces the swellability of the lignocellulosic fibres. In the presence of oxidation, cross-linking of cellulose is enhanced by formation of hemiacetal groups by the carbohydrate chains. Although heat treatment is a physical process, but it leads to the modification of the fibre surface

Table 1
Typical properties of saturant as supplied by the manufacturer.

Mechanical property	MBrace saturant
Description	2 Parts; Part A-epoxy and Part B-hardener
Density	1.06 kg/lt (Mixed density)
Colour	Blue
Bond strength	>2.5 N/mm^2 (Failure in concrete)

Figure 1. (a) Samples in oven for high temperature conditioning; (b) thermostatically controlled oven used for heat treatment of woven natural fabrics.

morphology, rather than changing the fibre internal structure. The crystallinity of the fibres could be attributed to the fact that, upon consistent heat treatment at 80 °C, for 48 h, the crystallinity of cellulose increases due to the rearrangement of molecular structure at elevated temperatures. Thermal treatment also results in moisture loss of the fabric thereby enhancing the extent of bonding between fabric and the natural rubber backing. As we know that demoisturization plays a vital role in enhancing mechanical properties, the overall properties of composites prepared with high temperature conditioned woven jute or sisal fibres are better than the composites prepared with untreated ones of the same woven fibres of jute or sisal. Also another important aspect for thermal conditioning is that the fibres are exposed to atmosphere during manufacturing, processing, transporting, etc, which results in the absorption of moisture by the fibres from the environment. This moisture which gets accumulated in the fibres also requires to be eliminated, and can be attained by the process of thermal conditioning.

2.3. Fabrication of composites

The woven sisal and jute fibre mats were cut in sizes as per the specifications of tensile test as per ISO 527-4, 1997(E) ISO 527-4, 1997 and carbon and glass fabrics were cut in sizes as per the specification of ISO 527-5:1997(E) ISO 527-4, 1997. Since jute and sisal both belong to Class II Type material, and carbon belongs to Class IV and glass belongs to Class III, all restrictions of the specimen dimensions for flexural testing as per the code ISO 14125:1998 (BS EN ISO14125, 1998) were followed, before subjecting the natural fibres to mechanical treatments themselves. A plastic bit mould of suitable dimension was used for casting the fabric composite sheets. The usual hand lay-up technique was used for the preparation of samples. A calculated amount of epoxy resin and hardener at a ratio 3:1 by weight was thoroughly mixed with gentle stirring to minimize air entrapment. For quick and easy removal of composite sheets, a mould releasing agent was used. Electrical Insulating Paper was put underneath the Plastic Bit Mould and mould release agent that as either poly-vinyl alcohol or silicone grease was applied at the inner surface of the mould. After keeping the mould on the insulating sheet, a thin layer (2 mm thickness) of mixture of epoxy and hardener was poured. Then the fabric mats were separately distributed on the mixture on different moulds. The remaining mixture was then poured into the mould on top of the fabric mats. Care was taken to avoid formation of air bubbles. Pressure was then applied from the top into the mould and with this pressure on top of the composite sheet; it was allowed to cure at room temperature for 48 h. After 48 h the samples were taken out from the mould and kept in an air tight container for further experimentation.

2.4. Mechanical testing

Two mechanical tests were performed for all the four different variety samples of fabric (or woven) composites of jute, sisal, carbon and glass. These two tests include tensile strength test and flexural strength test. The tensile test was carried out by applying uni-axial load through both the ends of the specimen, using suitable jaws as an attachment to the UTM (universal testing machine). The tensile test was performed in the HEICO Digital Universal Testing Machine and results were obtained digitally with the aid of the digital data acquisition system. The dimensions of the specimens were as per ISO standards. The tensile strength test for jute and sisal fabric composites were done in accordance to ISO 527-4, 1997(E). The tensile strength test for both carbon and glass textile composite was done in accordance to ISO 527-5:1997(E). All the results were taken as an average value of 5 samples each. Fig. 2 shows the tensile testing arrangement and also the tensile fractures in all the FRP composite samples. Various types of fractures were observed in the textile composite samples, diagonal fracture as well as straight fracture perpendicular to the textile direction was observed in the case of sisal and jute textile FRP and uneven tearing fracture was observed in the case of carbon and glass FRP. All these types of fractures are accepted modes of tensile fracture in accordance to ISO 527-4, 1997(E) and ISO 527-5:1997(E), respectively. After the tensile strength tests, the flexural strength of the textile composites was deter-

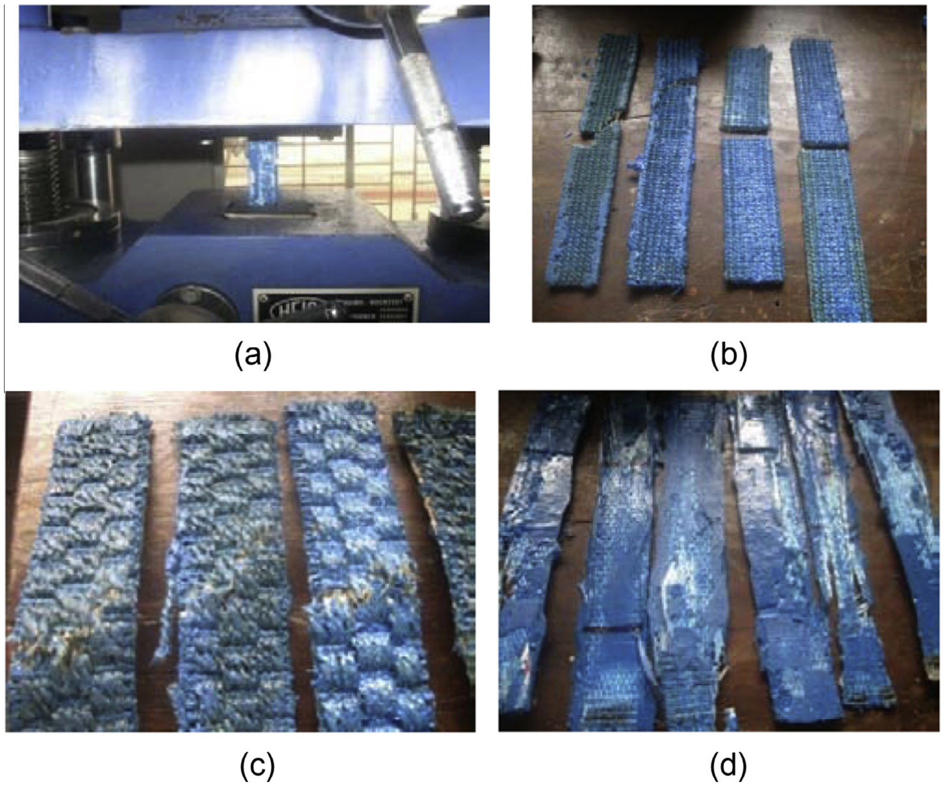


Figure 2. (a) Tensile testing of woven FRP; (b) tensile fracture samples of jute FRP; (c) tensile fracture samples of sisal FRP; (d) tensile fracture samples of carbon and glass FRP.

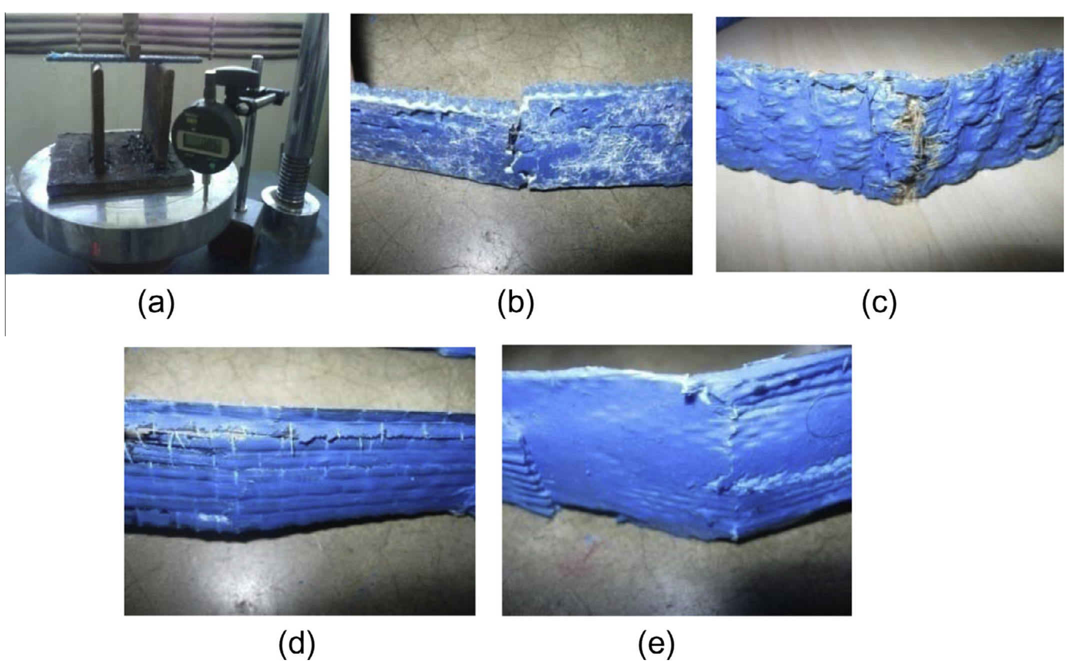


Figure 3. (a) Flexural testing of woven FRP; (b) flexural fracture sample of jute FRP; (c) flexural fracture sample of sisal FRP; (d) flexural fracture sample of carbon FRP; (e) flexural fracture sample of glass FRP.

mined. The flexural strength of a composite is a 3-point bend test, which generally promotes failure by inter-laminar shear. This test was conducted as per ISO 14125:1998 standard, using a load cell of high sensitivity. Fig. 3 shows the flexural testing arrangement and also the flexural fractures in all the FRP composite samples. After the flexural failure occurred, all specimens of the composites showed a single line fracture (perpendicular to the plane of the textile com-

Table 2
Tensile strength and flexural strength property of all types of woven FRP composites.

Type of FRP composite	Peak tensile load (kN)	Cross sectional area (mm^2)	Average peak tensile load (kN)	Average tensile strength (N/mm^2)	Peak flexural load (kg)	Peak deflection (mm)	Average peak flexural load (N)	Average flexural stress (N/mm^2)
Control or untreated jute FRP	7.63	91.25	7.65	83.836	27.5	2.87	264.87	127.711
	7.52	91.25			26	2.61		
	7.76	91.25			26.5	2.72		
	7.69	91.25			28	2.76		
Heat treated jute FRP	17.84	91.25	17.29	189.479	42.5	4.55	426.735	208.705
	16.65	91.25			43	4.66		
	17.24	91.25			44	4.42		
	17.43	91.25			44.5	4.53		
Control or untreated sisal FRP	10.68	99.50	10.71	107.638	52.5	2.48	519.93	210.523
	10.74	99.50			52.4	2.65		
	10.76	99.50			53.6	2.58		
	10.66	99.50			53.5	2.55		
Heat treated sisal FRP	22.12	99.50	22.225	223.367	77.5	10.72	760.275	350.034
	22.34	99.50			77.5	10.89		
	22.23	99.50			77.9	10.83		
	22.21	99.50			77.1	10.78		
Carbon FRP	16.34	18	16.615	923.056	46	8.69	451.26	1587.134
	16.89	18			45	8.77		
	16.72	18			46	8.68		
	16.51	18			47	8.78		
Glass FRP	14.32	21	14.25	678.571	25.5	3.45	313.92	666.871
	14.18	21			26	3.88		
	14.23	21			25	3.74		
	14.27	21			26.5	3.59		

posite direction). Table 2 gives the values of the tensile strength and flexural strength of the different types of treated and untreated FRPs of sisal and jute, along with the values of artificial FRPs of carbon and glass. Fig. 4 presents the comparative graphical variation of the ultimate tensile strengths and the moduli of elasticity of all FRP composite samples.

3. Durability study of FRP composites

While most of us have a general sense of what the term ‘durability’ means, it is not easily defined in the context of infrastructure materials and numerous definitions have been proposed in the literature. In the current educational module durability is defined on the basis of a definition offered by Karbhari et al. (1997, 2007) as the ability of an FRP element: “to resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental condition.” The available data on the durability of FRP materials are somewhat limited and can thus appear contradictory in some cases. This is due to the many different forms of FRP materials and fabrication processes currently used. Furthermore, FRPs used in civil engineering applications are substantially different from those used in the aerospace industry, and hence their durability cannot be assumed to be the same. All engineering materials are subject to mechanical and physical deterioration with time, load, and exposure to various harmful environments. Here durability study of sisal, jute, carbon and glass FRP composites were evaluated under three most common environmental conditions of civil infrastructure:

3.1. Effect of normal water

The mechanical properties of thermoset resin matrix composite materials are affected when exposed to wet environments. The absorbed water causes matrix plasticization and or interface degradation. The effect of water environment on moisture absorption characteristics of the different composite materials has been investigated by the measurement and analysis of percentage moisture content, thickness swelling and effect of water on the tensile strength property of sisal, jute, carbon and glass FRP composites. Firstly the composites were weighed and their thicknesses were measured. Normal water was then collected and heated (till bubbles started appearing) to 100^0 C along with the composites for 30 min, then the composites were removed from the hot water, and wiped with cotton and then weighed again, and their thicknesses were measured. The relative mass change of the epoxy in the specimens under study was expressed as a percentage obtained using the expression: Moisture content = (weight of soaked specimen – weight of dry specimen)/weight of dry specimen. Thickness swelling index was also measured by measuring the thickness of the composites before and after boiling. Lastly tensile strength tests were carried out on these composite samples. It was observed that the moisture content percentages were 5.9% for sisal, 6.6% for jute, 1.4% for carbon and 0.6% for glass FRP composites. Natural FRP composites displayed a higher moisture content than artificial FRP composites. Thickness swelling percentages were 2.7% for sisal, 8.9% for jute, 7% for carbon and 7% for glass FRP composites. Sisal FRP composite displayed the least thickness swelling index. The tensile strength of all the FRP composites underwent an increment in the wet conditions as compared to the dry conditions. The tensile strength increased by 6% for sisal, 8% for jute, 1.3% for carbon and 1% for glass FRP composites. All the FRP composites i.e. both natural and artificial FRP composites displayed similar trends and behaviour under the effect of water. The hydro-thermal effects on the various FRP composites could be as a result of two mechanisms. Firstly, at the macroscopic level, the expansion of the matrix due to

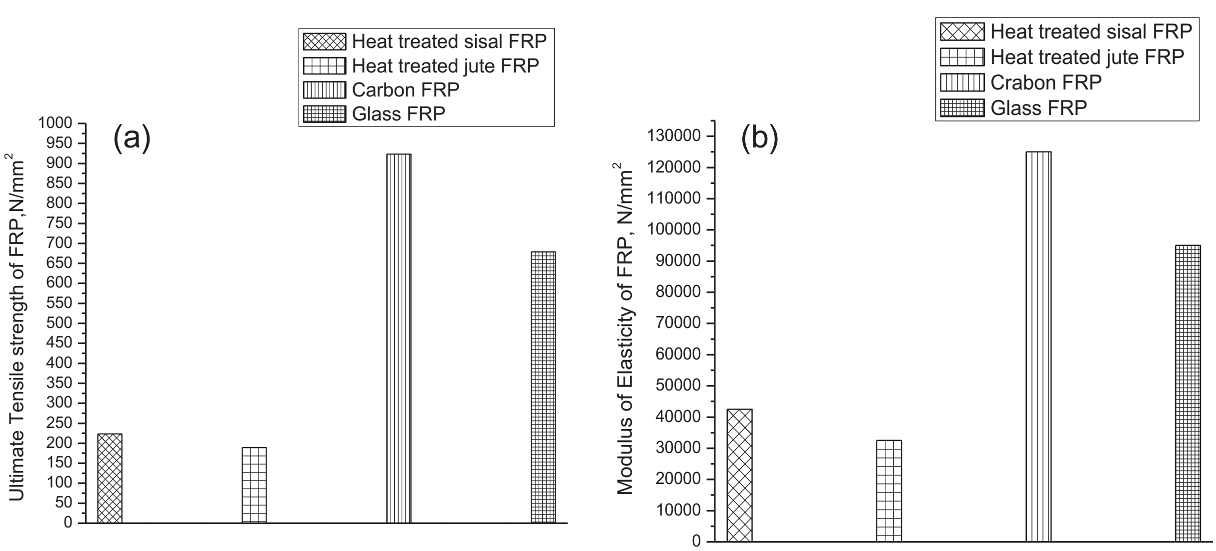


Figure 4. (a) Ultimate tensile strength of all woven FRP composites; (b) modulus of elasticity of all woven FRP composites.

absorption of water may cause tensile stresses in the fibres and compressive stresses in the matrix which is similar to differential thermal expansion. Secondly, at the molecular level, the diffusing molecules of water may strain or rupture the intermolecular bond in the matrix and at the interface.

3.2. Effect of thermal ageing

Thermal ageing behaviour of composite is of special interest because of their expanding use for structural applications where increased temperatures are common environmental condition. There are significant chemical and structural changes in epoxy networks which take place during thermal ageing. Delamination and micro cracking are some of the most frequently observed damaging phenomena that may develop in polymer composites exposed to cryogenic temperatures (low temperature conditions). Two batches of samples were fabricated for this test. The first batch of samples were kept at a temperature of +75 °C (in oven) for 10 hours, and the second batch of samples were exposed to ultra-low deep freezing conditions at −75 °C temperature, in the freezer for 6 h, these were followed by tensile strength testing for both the batches of the samples immediately. It was observed that the tensile strength of the various woven FRP composites underwent an increment under high temperature i.e.+75 °C conditions and came down under low temperature i.e. −75 °C conditions. Tensile strength enhanced by 8% for sisal, 7% for jute, 2% for carbon and 2.5% for glass FRP composites under +75 °C conditions, and tensile strength decreased by 14% for sisal, 12% for jute, 4.5% for carbon and 5.5% for glass FRP composites under −75 °C conditions. The most common damage modes in thermal ageing are matrix cracking, delamination growth and fibre fracture. Cryogenic exposure introduces matrix cracking and/or interfacial debonding. During cryogenic conditioning the fibre/matrix adhesion is low. So the first form of damage in laminates is commonly matrix micro cracks and inter-laminar cracks at such low temperature conditions. This is one of the reasons for the decrease in the tensile strength of composites, when subjected to very low temperatures. Thermal conditioning at higher temperatures, imparts better adhesion and thus improved tensile strength values are observed, since fibre cross linking is highly probable during thermal conditioning, when the composites are exposed to higher temperatures, hence, it increases the tensile strength of the composites. Both the natural fibre composites and the artificial fibre composites behaved similarly under the thermal ageing test conditions.

3.3. Fire flow test

Fire flow study of any material is very important for constructional performance, from the study we can easily know, if any fire related accident happens, how fast the fire can flow with respect to time considering the building material, and how can we reduce the flow rate of fire, and what will be the effect in environment when those particular materials get fire. This test was performed in accordance to ASTM D635 standard, and the burning rate was measured. The average burning rates displayed were 12 mm/min for sisal, 10 mm/min for jute, 51 mm/min for carbon, and 28 mm/min for glass FRP composites. Natural FRP composites displayed the lowest burning rates as compared to artificial FRP composites, hence the fire behaviour of natural FRP composites was far better as compared to artificial FRP composites. Natural FRP composites were basically thicker than artificial FRP composites, hence the thick layer of the composite acted as a heat sink, and also as an insulating layer, thus slowing down the burning rate as compared to thin FRP composites.

4. Methods

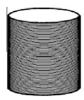
4.1. Details of concrete cylinder specimens

A total of 18 cylindrical concrete specimens, all with 103 mm diameter and 200 mm height were cast, and cured for 28 days before being tested. The target compressive strength of the mix was 20 MPa. Out of the 18 cylinders cast, 2 cylinders were selected as control specimens, where no FRP wrapping was carried out. The rest of the cylinders were cast in 2 batches of 8 each. The first 9 cylinders were FRP wrapped throughout their entire diameter, i.e. fully FRP wrapped. The second batch of 9 cylinders was FRP wrapped, so as to achieve 50% of wrapping configuration. The entire summary of all the model specimens along with their different confining configurations are described in Table 3. In the present work, ordinary Portland cement of 53 grade, i.e. ACC cement of grade 53 conforming to IS:12269-1987 had been used. Locally available clean river sand was used in this work. The maximum size of coarse aggregate used was 12 mm. The mix proportion of the concrete was in accordance to IS:10262-2009, in order to achieve the concrete target compressive strength of 20 N/mm^2, with the mix proportion by weight of cement:sand:coarse aggregate being 1:2.07:1.87.

4.2. Wrapping procedure of natural and artificial FRPs on cylinder specimens

The surface preparation of the cylinders for confinement was carried out after 28 days, i.e. after the concrete had attained full 28 days of curing strength. The concrete cylinders were prepared by grinding their entire cylindrical surfaces with the help of a grinding machine. This was done so as to roughen the surfaces of all concrete cylinders where FRP wrapping would be successively carried out. After grinding, the surfaces were cleaned with an air nozzle, and finally wiped to remove any dust or loose particles. Small surface defects in concrete cylinders which may arise due to manual casting techniques, were repaired and made good using concresive 2200. Then a coat of MBrace® primer was applied on the entire side surface of the concrete

Table 3
Summary of all the concrete cylinders along with their wrapping configuration.

Cylinder group	Confinement configuration	Strengthening material	Number of FRP layers	Beam designation (Two numbers of models under each category)
Group A	Nil	Nil	One	Control1, Control2
Group B	Full wrapping and confinement	Sisal FRP	One	SisalF1, SisalF2
		Jute FRP	One	JuteF1, JuteF2
		Carbon FRP	One	CarbonF1, CarbonF2
		Glass FRP	One	GlassF1, GlassF2
Group C	Strip wrapping and confinement	Sisal FRP	One	SisalS1, SisalS2
		Jute FRP	One	JuteS1, JuteS2
		Carbon FRP	One	CarbonS1, CarbonS2
		Glass FRP	One	GlassS1, GlassS2

cylinders. The primer coat was allowed to air cure for 8 h. Next, Resin Part A and Hardener Part B of the two component MBrace® saturant were mechanically premixed as per the guidelines of the BASF manufacturer for 3 min or until homogeneous. The ratio of mixing of resin and hardener was 3:1. Firstly, one coat of epoxy resin-hardener mix was applied throughout the entire diameter of the concrete cylinders for full wrapping configuration, and also in the measured strip surfaces along the diameter of the cylinders for strip wrapping configuration. Then the respective natural and artificial fabrics were all placed on top of the respective concrete cylinders, and another coat of epoxy resin- hardener coating was placed immediately on the respective cylinder models and the resin was squeezed through the roving of the fabric with plastic laminating roller. The entire summary of all the models as described in Table 3 was observed and followed for the wrapping and confinement configuration. It was made sure that all fabric reinforcements were properly impregnated within the resin hardener mix. Air bubbles entrapped at the epoxy/concrete or epoxy/fabric interface were all eliminated. All the FRP confined concrete cylinders were cured for at least two weeks at room temperature before they were finally tested. The entire FRP confining process that is surface preparation of concrete cylinders and bonding of respective natural or artificial FRPs in full confinement or strip confinement, along with top most coat of epoxy-hardener, has been clearly presented in Fig. 5. Also it is to be mentioned that only one FRP layer was used in a single layer and it was applied for all cylinders in one continuous manner without any discontinuity, with one overlapping zone.

4.3. Axial compression testing

Axial compressive tests on the controlled or unconfined cylinder specimens were carried out after the 28 day strength of concrete was attained. Also, the axial compressive tests on the FRP-confined concrete cylinders were carried out after 14 days of air curing after the FRP confinement or wrapping process. The axial compressive test on all the concrete controlled or unconfined cylinders as well as the FRP confined cylinders were carried out in the universal testing machine (UTM) by HEICO (Fig. 6). The rate of application of loading was 2 mm/min. The entire axial loads carried by the concrete specimens along with their corresponding axial deformations were recorded with the help of the digital data acquisition system. The recorded axial loads (kN) were used in the calculation of the percentage increase in the axial load carrying capacity due to confinement provided by natural fabric composites of sisal and jute, and artificial fabric composites of carbon and glass. To ensure an even loading surface a thin layer of capping material was applied at the top surface of the concrete cylinder, for uniform distribution of load. This is essential so as to ensure that axial stress concentration does not occur at a particular location. The load was applied directly on the concrete cylinder through thick cut steel discs. It was also made sure that the sizes of the discs were at least equal to or greater than the nominal size of the concrete cylinders. All cylinders were placed such that there would be no generation of eccentricity while the axial load would act.

4.4. Confinement strength and modulus study

Ductility of a structure, or its members, is the capacity to undergo large inelastic deformations without significant loss of strength or stiffness. Ductility is that parameter which enables large deformations of any structural component before failure. If ductile members are used to form a structure, the structure can spread out suitable warnings prior to its collapse. This is beneficial to the users of the structures, as warnings are generated to the occupants in order to ensure lesser damage to life. Ductility is an essential attribute and property of an earthquake resistant structure. Ductility is that parameter which reduces the dynamic load demand through increased energy dissipation. This phenomenon has had a profound significance in the design of structures in seismic regions for at least the last half a century. A very important interlinked parameter of structural ductility is the confinement property. Enhancement in confinement of a structural component directly related to an increase in the ductility of the component. Confinement is the process of restraining the concrete by means of closely-spaced special transverse reinforcement in directions perpendicular to the applied stress. Confinement is the most popularly used characteristics for enhancing the ductility of building columns. As columns are the most significant load carrying members of any structural frame system, their energy dissipation capacity without collapse, ensuring safety is a very integral characteristic of the structural system. And the same can be ensured by suitable confinement of these important structural components. The most common types of confinement are steel confinement, reinforced concrete confinement, fibre reinforced polymer composite confinement, confinement with high tension materials like carbon fibre, glass fibre, etc. Confinement with newer sustainable green composite materials such as natural fibre composite confinement can also be researched upon. Confinement basically encases the concrete and provides confinement by view of transverse fibre or reinforcements, especially for circular cross sectional concrete columns. Confinement also increases the flexural strength by virtue of well anchored longitudinal fibres or reinforcement at critical sections.

Confinement modulus (E_l) and confinement strength (f_l) of FRP are considered to be the two main factors affecting the performances of FRP-confined concrete cylinders. As FRP composites are often linear elastic materials, equations to calculate confinement modulus and confinement strength can be derived based on the equilibrium and deformation compatibility conditions (Xiao and Wu, 2001; Wu, 2002; Wu et al., 2006). Confinement modulus is given by $E_1 = \frac{1}{2}\rho_f E_f$, and the confinement strength is given by $f_1 = \frac{1}{2}\rho_f f_f$ in accordance with various studies conducted on FRP confined concrete cylinders (Xiao and Wu, 2001; Wu, 2002; Wu et al., 2006).

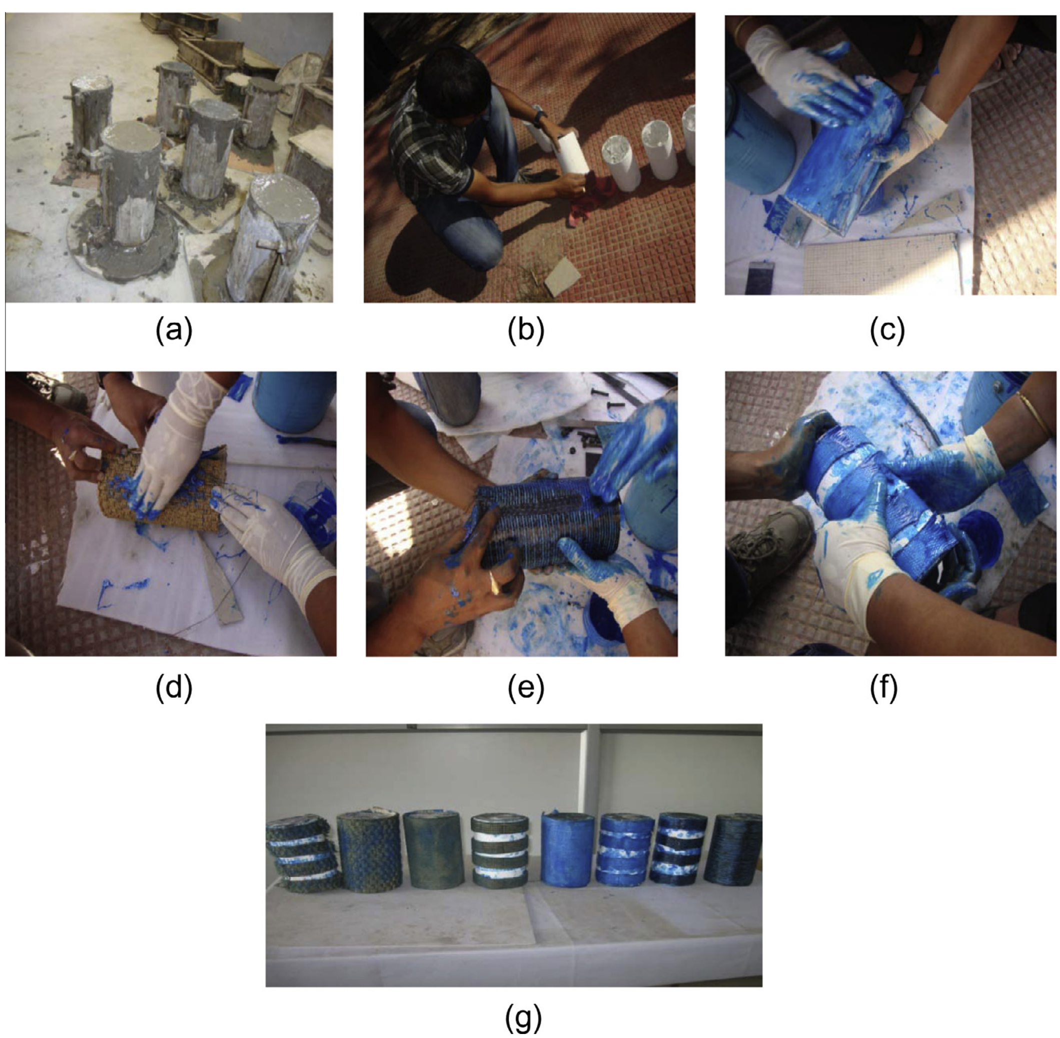


Figure 5. (a) Concrete cylinders after casting; (b) primer applied concrete cylinders being cleaned; (c) application of epoxy hardener mix on the concrete cylinder; (d) bonding of woven sisal fabric on the cylinder; (e) final coating of epoxy hardener mix on the bonded carbon fabric on the concrete cylinder; (f) final coating of epoxy hardener mix on the strip bonded glass fabric on the concrete cylinder; (g) all the FRP confined concrete cylinders before testing.

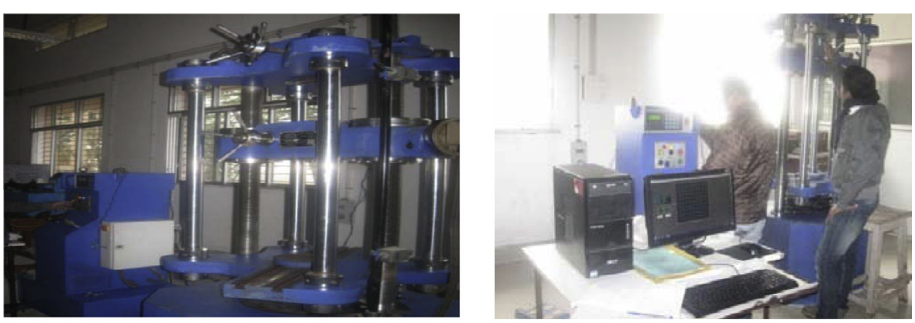
Here E_f is the modulus of elasticity of FRP; f_f is the ultimate tensile strength of FRP; and ρ_f is the volumetric ratio of FRP to concrete, which can be determined by $\rho_f = \frac{4t_f}{D}$ for fully FRP wrapped concrete cylinder and by $\rho_f = \frac{4t_f b_f}{D(b_f+s_f)}$, for partially FRP wrapped concrete cylinder. Also here t_f is the thickness of FRP, D is the diameter of concrete cylinders, b_f is the width of FRP strip, and s_f is the clear vertical spacing between strips for partially wrapped FRP concrete cylinders.

The confinement modulus and the confinement strength of fully FRP wrapped concrete cylinders are presented in Table 4 and the confinement modulus and the confinement strength of partially FRP wrapped concrete cylinders are presented in Table 5. Fig. 7(a) and (b) presents the comparative graphical variation in the confinement modulus and the confinement strength respectively for differently FRP confined concrete cylinders with respect to full confinement and partial confinement.

5. Test results

5.1. Axial compressive load carrying capacity

The ultimate condition of failure of the concrete cylinders, which is basically comprised of the ultimate axial strength of both the FRP confined and the controlled or unconfined cylinders were recorded at the failure of the specimen, and all the corresponding ultimate axial deflections too were recorded digitally by the data acquisition system. The ultimate axial loads along with the axial deflections of the corresponding FRP confined and unconfined concrete cylinders subjected to axial compression are presented in Table 6 for fully FRP wrapped concrete cylinders, and the same are presented in Table 7 for partially FRP wrapped concrete cylinders. The ultimate axial load of each specimen was calculated by averaging the ultimate loads obtained for duplicate specimen models, as described in the stated Tables. The ultimate failure axial load was easily recorded for artificial FRP wrapped fully confined cylinders. As after the ultimate failure, no further load carrying capability in the specimens were observed. But for natural fabric composite fully wrapped cylinders, marking the ultimate failure axial load was a difficult task. Especially sisal fabric wrapped cylinders, the specimens displayed signs of failure, but again recovered to undergo further axial deflection before undergoing failure. Similar behaviour was also displayed by jute fabric composite fully wrapped cylinders, but the recovery of sisal fabric composite fully wrapped cylinders before ultimate failure was more superior. This proves that sisal fabric composite cylinders displayed post axial load peak ductile behaviour before reaching the highest axial deformations at higher axial loads. It is evident from the experimental results obtained that the confining



(a) (b)

Figure 6. (a) Instrument used for compressive testing of cylinders; (b) the instrument along with the digital data acquisition system.

Table 4
Confinement modulus and strength properties of fully wrapped concrete cylinders.

Type of specimen fully wrapped	Depth D of the cylinder (mm)	FRP composite thickness t_f (mm)	Volumetric ratio $\rho_f - \frac{4t_f}{D}$	Modulus of elasticity of FRP E_f(kN/mm^2)	Ultimate tensile strength of FRP f_f (N/mm^2)	Confinement modulus (N/mm^2) $E_1 = \frac{1}{2}\rho_f E_f$ (N/mm^2)	Confinement strength (N/mm^2) $f_1 = \frac{1}{2}\rho_f f_f$(N/mm^2)
SisalF1	103	3.98	0.155	42.5	223.367	3293.75	17.32
SisalF2	103	3.98					
JuteF1	103	3.65	0.142	32.5	189.479	2307.5	13.46
JuteF2	103	3.65					
CarbonF1	103	1.2	0.047	125.0	923.056	2937.5	21.7
CarbonF2	103	1.2					
GlassF1	103	1.4	0.055	95.0	678.571	2612.5	18.67
GlassF2	103	1.4					

Table 5
Confinement modulus and strength properties of partially wrapped concrete cylinders.

Type of specimen Partially wrapped	Width of FRP strips b_f (mm)	Net spacing between the FRP strips s_f (mm)	Volumetric ratio $\rho_f = \frac{4t_f b_f}{D(b_f+s_f)}$	Modulus of elasticity of FRP E_f (kN/mm^2)	Ultimate tensile strength of FRP f_f (N/mm^2)	Confinement modulus $E_1 = \frac{1}{2}\rho_f E_f$ (N/mm^2)	Confinement strength $f_1 = \frac{1}{2}\rho_f f_f$ (N/mm^2)
SisalS1	30	26.67	0.082	42.5	223.367	1742.5	9.16
SisalS2	30	26.67					
JuteS1	30	26.67	0.076	32.5	189.479	1235	7.21
JuteS2	30	26.67					
CarbonS1	30	26.67	0.025	125.0	923.056	1562.5	11.54
CarbonS2	30	26.67					
GlassS1	30	26.67	0.029	95.0	678.571	1377.5	9.84
GlassS2	30	26.67					

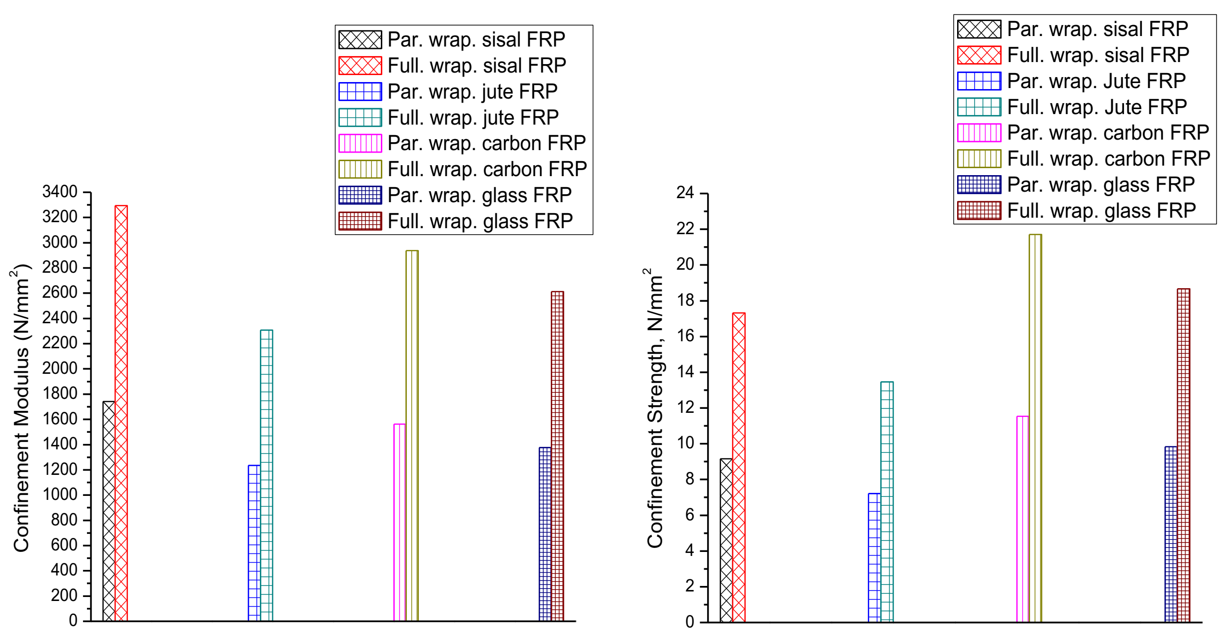


Figure 7. (a) Confinement modulus of different FRP confined concrete cylinders in view of fully and partially wrapping techniques; (b) confinement strength of different FRP confined concrete cylinders in view of fully and partially wrapping techniques.

Table 6
Result summary of axial compressive test conducted on fully wrapped concrete cylinders.

Type of specimen	Axial deflection at failure (mm)	Average axial deflection at failure (mm)	Ultimate axial load (kN)	Average ultimate axial load (kN)	Percentage increase in axial load carrying capacity
Control1	2.23	2.86	119.92	118.26	–
Control2	3.48		116.59		
SisalF1	10.56	12.01	197.35	196.52	66.18
SisalF2	13.45		195.68		
JuteF1	7.97	8.12	174.82	175.64	48.53
JuteF2	8.26		176.45		
CarbonF1	4.12	4.45	215.55	217.4	83.84
CarbonF2	4.78		219.24		
GlassF1	6.58	6.73	334.75	332.28	180.98
GlassF2	6.87		329.81		

action of natural fabrics of sisal and jute composite on the axial load carrying capacity of concrete cylinders is of a good magnitude. And as the extensive research literature has it, CFRP and GFRP composite wrapping too greatly enhanced the axial load carrying capacity of concrete cylinders. The performance of sisal fabric composite wrapping

Table 7
Result summary of axial compressive test conducted on partially wrapped concrete cylinders.

Type of specimen	Axial deflection at failure (mm)	Average axial deflection at failure (mm)	Ultimate axial load (kN)	Average ultimate axial load (kN)	Percentage increase in axial load carrying capacity
Control1	119.92	118.26	2.23	2.86	–
Control2	116.59		3.48		
SisalS1	153.45	155.16	4.11	5.15	31.21
SisalS2	156.87		6.18		
JuteS1	136.72	136.1	3.11	3.82	15.09
JuteS2	135.48		4.53		
CarbonS1	173.52	172.13	3.77	3.65	45.56
CarbonS2	170.74		3.52		
GlassS1	222.38	223.52	6.11	6.02	89.01
GlassS2	224.65		5.92		

came very close to the performance as displayed by artificial FRP composite wrappings. All concrete cylinders exhibit highly ductile behaviour when sufficiently confined by either FRP wraps, since the characteristics of axial load carrying capacities are better and superior for fully wrapped cylinders than for partially wrapped ones. Partially confined specimens exhibit gains in strength or ductility, between those for the controlled or unconfined cylinders and the fully FRP wrapped cylinders. The fully FRP confined specimens displayed highest axial load carrying capacity. Hence we can conclude that an increase in the amount of confinement results in an increase in the ultimate axial load. Fig. 8 presents the comparative graphical variation in the ultimate axial load for different FRP confined concrete cylinders with respect to full confinement and partial confinement, and also the same for controlled or unconfined concrete cylinders.

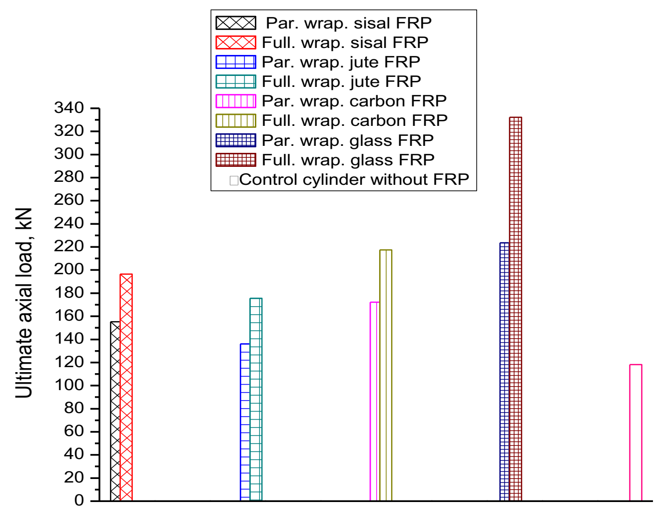


Figure 8. Ultimate axial load of different FRP confined concrete cylinders in view of fully and partially wrapping techniques and their comparison with the unconfined controlled or unconfined cylinder.

5.2. Failure modes of the concrete cylinders

The observed failure modes of all fully confined and partially confined concrete cylinder specimens are clearly presented in Fig. 9. For Control1 and Control2, the ultimate failure was reached by excessive concrete cracks throughout the height of these specimens. These models went on absorbing the axial load and dissipated the load all around the diameter throughout their heights, since no confinement was present. The ultimate rupture was evident, when these models failed to take any further axial load, with a large number of longitudinal cracks. The fully FRP confined specimens displayed the highest axial load carrying capacity. In SisalF1 and F2, the ultimate failure modes were marked by the continuous rupture of the FRP laminate from top to the bottom in a single line crack formation, without the generation of any other alternate crack. This rupture of FRP started from the top surface and followed until the bottom was reached, once FRP failure was initiated, concrete from the concrete cylinder opened up and there was concrete disruption and burst along the unconfined portion of the concrete cylinder, due to the FRP rupture. Although rupture of sisal FRP took place, there was absolutely no debonding of the FRP from the faces of the concrete cylinder. JuteF1 and F2 displayed a similar type of failure mode as displayed by SisalF1 and F2, i.e., a single line fracture of FRP without any debonding. But the concrete burst or disruption after the FRP single line fracture was much more prominent in JuteF1 and F2 as compared to SisalF1 and F2. As is evident from the figures, the ultimate failures of natural FRP confined concrete cylinders were due to shear cone formations, because of the effect of axial compression on the FRP confined concrete. In all cases shear cone formations were observed. And failures were marked by concrete burst through the unconfined portion of the cylinder due to the FRP rupture. This type of rupture where the rupture in the FRP laminate originates from the top surface and continues throughout the bottom in a single line is called continuous laminate rupture, which was evident, in both the failure modes of SisalF1 and F2 as well as JuteF1 and F2. In CarbonF1 and F2, the ultimate failure modes were marked by the continuous rupture of the FRP laminate in a ringed formation in the bottom half. This type of FRP rupture where the rupture is predominant in any particular

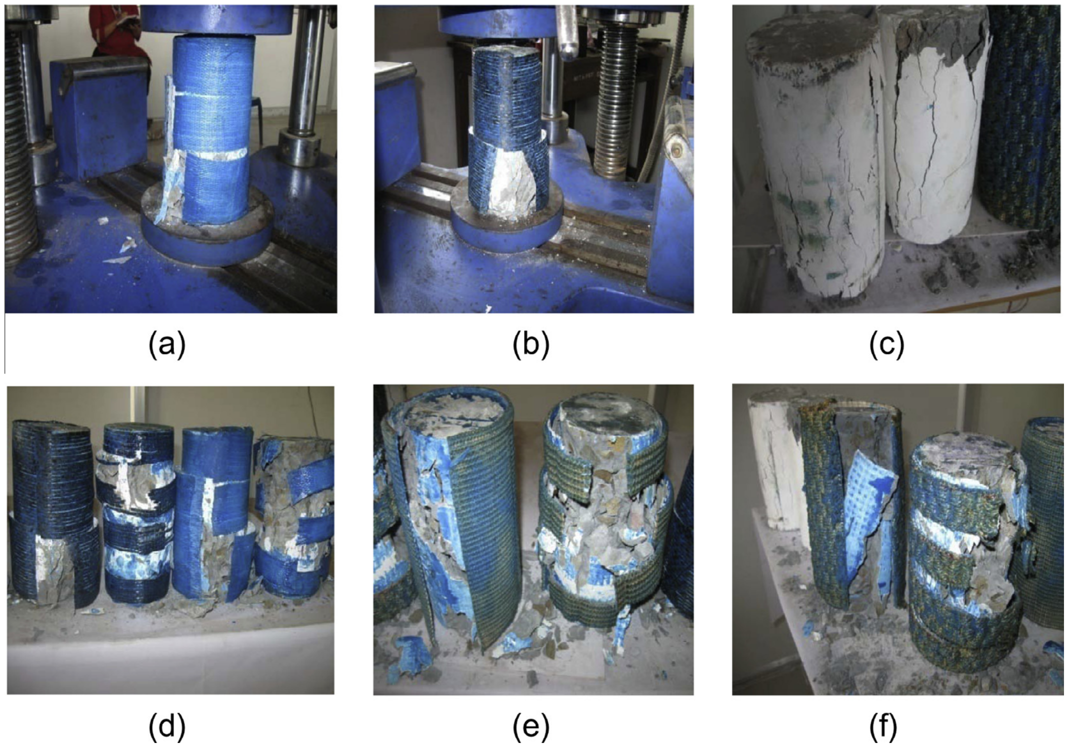


Figure 9. (a) Ultimate failure modes of GlassF1 under axial compression; (b) ultimate failure modes of carbonF1 under axial compression; (c) failure modes of unconfined concrete cylinders Control1 and Control2; (d) ultimate failure modes of CarbonF1, CarbonS1, GlassF1 and GlassS1; (e) ultimate failure modes of JuteF1 and JuteS1; (f) ultimate failure modes of SisalF1 and SisalS1.

location, is called cross sectional rupture of the FRP at that particular location. Here it was observed that both CarbonF1 and F2, underwent failures by shear cone formations, which led to bottom half rupture of CFRP, followed by concrete burst and disruption from the bottom concrete cross section due to the loss of confinement action due to FRP rupture. Here the stress concentrations at the bottom cross section due to the shear cone formation altogether led to the concentration of localized stresses in the bottom half which successively promoted failure in the CFRP fully wrapped concrete cylinders. In GlassF1 and F2, the ultimate failure modes were marked by the ringed rupture of the GFRP laminate in a ringed formation throughout the entire height of the concrete cylinder. This type of FRP rupture where the rupture basically takes place in the form of closed circular rings, due to excessive generation of circumferential stresses is called ringed rupture of the FRP. Here it was observed that both GlassF1 and F2, underwent failure due to the shear cone formations, which led to the generation of large amounts of circumferential stresses, followed by ringed type of FRP rupture throughout the entire height of the concrete cylinders. This was duly followed by concrete burst and disruption in rings wherever the confining action was lost due to FRP rupture. This case of axial compressive failure is very common because of the conglomeration of excessive circumferential or hoop stresses generated by heavy axial loadings. Here the large amounts of circumferential stresses led to the formation of ringed type of failure throughout the entire height of these models, and successively promoted failure in the GFRP fully wrapped concrete cylinders. All the strip wrapped models displayed localized rupture of FRPs in the strips, especially in the strips present in the central zones, for the entire strip FRP confined concrete cylinder specimens. Concrete burst and disruptions were observed after the failure of the FRP strips in the central part of the cylinders. Here, too the ringed FRP rupture, due to the shear cone formations, followed by concrete burst were observed for all the strip FRP wrapped cylinders subjected to axial compression. The ultimate failure modes were marked by FRP strip ruptures, with complete disruption of concrete and inability of these specimens to carry any further load.

6. Conclusions

1. The thermally conditioned woven FRP composites of sisal and jute FRP exhibited the highest tensile strength. Heat treated sisal FRP composites displayed the highest tensile strength of 223 N/mm^2 and flexural strength of 350 N/mm^2, whereas heat treated jute FRP composites displayed a tensile strength of 189 N/mm^2 and flexural strength of 127 N/mm^2. It was observed that the tensile strength as well as the flexural strength of woven natural fibre composites enhanced with high temperature conditioning due to better cross-linkage, better adhesion

characteristics, and de-moisturization. The study showed that the reinforcement of woven sisal and jute fibre reinforced polymer composites created a new material with generally improved mechanical properties.

2. Basically the artificial FRP composites made up of woven fibres of carbon and glass displayed higher mechanical strengths than natural fibre composites. Carbon FRP composites displayed the highest mechanical properties among all FRP composites, with a tensile strength of 923 N/mm^2 and flexural strength of 1587 N/mm^2, followed by glass FRP composites, which displayed a tensile strength of 678 N/mm^2 and a flexural strength of 666 N/mm^2.
3. It was observed that the confinement strength of sisal FRP fully confined cylinders was 17 N/mm^2 and came very close to GFRP confinement strength, which had a confinement strength value of 18 N/mm^2. The highest confinement strength was displayed by CFRP confined cylinders at 21 N/mm^2, and jute FRP confined concrete cylinders displayed the least FRP confinement strength of 13 N/mm^2. The performance of natural FRP confinement especially that of woven sisal FRP confinement strength characteristics is of comparable magnitude to GFRP confinement strength characteristics. Hence, we can conclude that even natural FRPs made up of woven sisal fibres, and their fabricated composites can be suitable for concrete confinement as it displays enough potential in terms of confinement strength characteristics.
4. It was observed that the confinement modulus of sisal FRP fully confined cylinders was 3294 N/mm^2 and it was the highest among all the other FRP confinements including carbon and glass and even jute. This was closely followed by the confinement modulus of carbon FRP fully confined cylinders, which was 2937 N/mm^2, further followed by glass FRP fully confined cylinders, which was 2612 N/mm^2. And finally the confinement modulus of jute FRP fully confined cylinders was 2307 N/mm^2. In spite of sisal FRP being fabricated from natural woven fibres of sisal, the material FRP displayed superior confinement modulus properties even better than CFRP and GFRP, and has proven to be one of the most ductile materials for FRP confinement.
5. When sufficiently confined, FRP confined concrete cylinders exhibited high axial compressive load carrying capacities and ductility characteristics. However if the confinement was partial or sparse or inadequate, then the axial load carrying capacity and also the ductility characteristics were degraded as full wrapping displayed a higher axial load carrying capacity than partial wrapping configurations.
6. The ultimate axial load of glass FRP fully confined cylinders was the highest i.e., 332 kN, and displayed an increase in the load carrying capacity by 180% over controlled or unconfined cylinders, which displayed an ultimate axial load of 118 kN. Carbon FRP fully confined cylinders followed GFRP confinement, displaying an ultimate axial load of 217 kN, and an increase in the load carrying capacity by 83% over controlled or unconfined cylinders. The reason behind GFRP confinement having a higher ultimate axial load carrying capacity may be because GFRP fabric was multi-directionally braided and CFRP fabric was uni-directionally braided. The ultimate axial load of sisal FRP fully confined cylinders was close to CFRP confinement displaying a value of 196 kN, and also displaying an increase in the load carrying capacity by 66% over controlled or unconfined cylinders. Jute FRP fully confined cylinders displayed the least ultimate axial load among all FRP confinement materials, displaying an ultimate axial load value of 175 kN, and an increase in the load carrying capacity by 48% over controlled or unconfined cylinders.
7. The natural woven fibre reinforced polymer composite materials such as woven sisal FRP or woven jute FRP, displayed huge potential in the enhancement of axial load carrying capacity of concrete cylinders, similar to CFRP and GFRP confinement attributes. The utilization of these natural materials which come with huge environmental and sustainable benefits must be encouraged in all spheres of structural applications, so that our dependencies on non-renewable fossil fuel products for various structural application purposes are curtailed. Sisal FRP and jute FRP have good confinement strength as well as confinement modulus and hence can be attributed as a good ductile material with superior mechanical properties. Their utilization in various civil and structural engineering fields would definitely help us in moving towards a sustainable greener environment with better rural development promoting bio-diversity.

Acknowledgement

The authors would like to thank Amrita Singh Sondhi, Diptanu Das, Goga Murtem, Pankaj Das, Rajesh Das and Tanmoy Dey, who performed the experimental programme reported in this study as part of their undergraduate thesis under department of civil engineering, National Institute of Technology, Agartala.

References

Ahmeda, K. Sabeel, Vijayarangan, S., 2008. Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites. J. Mater. Process. Technol. 207, 330–335.

Alamri, H., Low, I.M., 2012. Mechanical properties and water absorption behaviour of recycled cellulose fibre reinforced epoxy composites. Polym. Testing 31, 620–628.

Barreto, A.C.H., Rosa, D.S., Fechine, P.B.A., Mazzetto, S.E., 2011. Properties of sisal fibers treated by alkali solution and their application into cardanol-based biocomposites. Composite A 42, 492–500.

Begum, K., Islam, M.A., 2013. Natural fiber as a substitute to synthetic fiber in polymer composites: a review. Res. J. Eng. Sci. 2 (3), 46–53.

Bledzki, A.K., Gassan, J., 1999. Composites reinforced with cellulose based fibres. Prog. Polym. Sci. 24, 221–274.

BS EN ISO14125, 1998. Fibre-reinforced plastic composites-determination of flexural properties Inc., Incorporating Technical Corrigendum No. 1.

Campos, A., Marconcini, J.M., Martins-Franchetti, S.M., Mattoso, L.H.C., 2012. The influence of UV-C irradiation on the properties of thermoplastic starch and polycaprolactone biocomposite with sisal bleached fibers. Polym. Degrad. Stabil. 97 (10).

Cristaldi Giuseppe, Latteri Alberta, Recca Giuseppe, Cicala Gianluca. 2015. Composites based on natural fibre fabrics. Book Chapter No. 17, Woven Fabric Engineering. <www.intechopen.com>.

Elsanadedy, H.M., Al-Salloum, Y.A., Abbas, H., Alsayed, S.H., 2012. Prediction of strength parameters of FRP-confined concrete. Composite B 43, 228–239.

Gassan, Jochen, Bledzki Andrzej, K., 1999. Possibilities for improving the mechanical properties of jute/epoxy composites by alkali treatment of fibres. Compos. Sci. Technol. 59, 1303–1309.

Gunes, Oguz, Lau, Denvid, Tuakta, Chakrapan, Büyüköztürk, Oral, 2013. Ductility of FRP–concrete systems: investigations at different length scales. Constr. Build. Mater. 49, 915–925.

Hota, Gangarao, Liang, Ruifeng, 2011. Advanced fiber reinforced polymer composites for sustainable civil infrastructures. International Symposium on Innovation & Sustainability of Structures in Civil Engineering Xiamen University, China.

Hussein, Mohamed, Kunieda, Minoru, Nakamura, Hikaru, 2012. Strength and ductility of RC beams strengthened with steel-reinforced strain hardening cementitious composites. Cement Concr. Compos. 34, 1061–1066.

ISO 527-4, 1997. Plastics-determination of tensile properties, part-4: test conditions for isotropic and orthotropic fibre-reinforced plastic composites.

ISO 527-5, 1997. Plastics-determination of tensile properties, part-5: test conditions for unidirectional fibre-reinforced plastic composites.

Issa, Mohamed S., Metwally, Ibrahim M., Elzeiny, Sherif M., 2011. Influence of fibers on flexural behavior and ductility of concrete beams reinforced with GFRP rebars. Eng. Struct. 33, 1754–1763.

Trdine, Janeza, Rijeka, Croatia, Copyright© 2010 Sciyo. Woven Fabric Engineering, Edited by Prof. Dr. Polona Dobnik Dubrovski. ISBN 978-953-307-194-7. Published November 2010.

John, Maya Jacob, Thomas, Sabu, 2008. Review of biofibres and biocomposites. Carbohydr. Polym. 71, 343–364.

Joshi, S.V., Drzal, L.T., Mohanty, A.K., Arora, S., 2004. Are natural fiber composites environmentally superior to glass fiber reinforced composites. Composite A 35, 371–376.

Kabir, M.M., Wang, H., Aravinthan, T., Cardona, F., Lau, K.T., 2011. Effects of natural fibre surface on composite properties: a review", eddbe. Proc. Energy Environ. Sustainability 2011, 94–99.

Kaewkuk, Sulawan, Sutapun, Wimonlak, Jarukumjorn, Kasama, 2010. Effect of heat treated sisal fibre on physical properties of polypropylene composites. Adv. Mater. Res., 123–125

Karbhari, V.M., Abanilla, M.A., 2007. Design factors, reliability, and durability prediction of wet layup carbon/epoxy composites used in external strengthening. Composite B 38, 10–23.

Karbhari, V.M., Eckel II, D.A.M., 1997. On the durability of composite rehabilitation schemes for concrete: use of a peel test. J. Mater. Sci. 32, 147–156.

Kim, Hyo Jin, Seo, Do Won, 2006. Effect of water absorption fatigue on mechanical properties of sisal textile-reinforced composites. Int. J. Fatigue 28, 1307–1314.

La Mantia, F.P., Morreale, M., 2011. Green composites: a brief review. Composite A 42, 579–588.

Langford, Laney Matthew, 2011. Sustainable Composites from Natural Materials. A (M.Sc. thesis). North Carolina State University (Submitted).

Li, Yan, Mai, Yiu-Wing, Ye, Lin, 2000. Sisal fibre and its composites: a review of recent developments. Compos. Sci. Technol. 60, 2037–2055.

Liu, X.Y., Dai, G.C., 2007. Surface modification and micromechanical properties of jute fiber mat reinforced polypropylene composites. eXPRESS Polym. Lett. 1 (5), 299–307.

López-Lara, T., Hernandez-Zaragoza, Juan Bosco, Horta, Jaime, Gonzalez, Eduardo Rojas, Lopez-Cajun, Carlos, Ramirez, Gerson, 2013. Sustainable use of tepetate composite in earthen structure. Adv. Mater. Sci. Eng., 6 (Article ID 806387)

Maria Ernestina, Fidelis Alves,, Thatiana Vitorino, Castro Pereira, Otávio da Fonseca, Martins Gomes, Flávio de Andrade, Silva, Romildo Dias, Toledo Filho, 2013. The effect of fiber morphology on the tensile strength of natural fibers. J. Mater. Res. Technol. 2 (2), 149–157.

Mathur, V.K., 2006. Composite materials from local resources. Constr. Build. Mater. 20, 470–477.

Meredith, James, Ebsworth, Richard, Coles Stuart, R., Wood Benjamin, M., Kirwan, Kerry, 2012. Natural fibre composite energy absorption structures. Compos. Sci. Technol. 72, 211–217.

Francesco, Micelli, Rossella, Modarelli, 2013. Experimental and analytical study on properties affecting the behavior of FRP-confined concrete. Composite B 45, 1420–1431.

Milanese, Andressa Cecília, Hilário Cioffi, Maria Odila, Cornelis Voorwald, Herman Jacobus, 2011. Mechanical behavior of natural fiber composites. Procedia Eng. 10, 2022–2027.

Milanese, Andressa Cecília, Hilário Cioffi, Maria Odila, Cornelis Voorwald, Herman Jacobus, 2012. Thermal and mechanical behaviour of sisal/phenolic composites. Composite B 43, 2843–2850.

Bedřich, Moldan, Janoušková, Svatava, Tomáš, Hak, 2012. How to understand and measure environmental sustainability: indicators and targets. Ecol. Ind. 17, 4–13.

Monteiro, Sergio Neves, Lopes, Felipe Perisse Duarte, Nascimento, Denise Cristina Oliveira, Ferreira, Ailton da Silva, Satyanarayana, Kestur Gundappa, 2013. Processing and properties of continuous and aligned curaua fibers incorporated polyester composites. J. Mater. Res. Technol. 2 (1), 2–9.

Munikenche Gowda, T., Naidu, A.C.B., Rajput, Chhaya, 1999. Some mechanical properties of untreated jute fabric-reinforced polyester composites. Composite: Part A 30, 277–284.

Nardone, Fabio, Di Ludovico, Marco, De Casoy, Basalo Francisco J, Andrea, Prota, Antonio, Nanni, 2012. Tensile behavior of epoxy based FRP composites under extreme service conditions. Composite B 43, 1468–1474.

Oehlers, D.J., Griffith, M.C., Mohamed Ali, M.S., 2009. Ductility components and limits of FRP-plated RC structures. Constr. Build. Mater. 23, 1538–1543.

Oehlers, D.J., Visintin, P., Haskett, M., Sebastian, W.M., 2013. Flexural ductility fundamental mechanisms governing all RC members in particular FRP RC. Constr. Build. Mater. 49, 985–997.

Pessiki, S., Harries, K.A., Kestner, J., Sause, R., Ricles, J.M., 2001. The axial behavior of concrete confined with fiber reinforced composite jackets. ASCE J. Comp. Constr. 5 (4), 237–245.

Ratna Prasad, A.V., Mohana Rao, K., 2011. Mechanical properties of natural fibre reinforced polyester composites: Jowar, sisal and bamboo. Mater. Des. 32, 4658–4663.

Ray, D., Sarkar, B.K., 2001. Characterization of alkali-treated jute fibers for physical and mechanical properties. J. Appl. Polym. Sci. 80, 1013–1020.

Rong, Min Zhi, Zhang, Ming Qiu, Liu, Yuan, Yang, Gui Cheng, Zeng, Han Min, 2001. The effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites. Compos. Sci. Technol. 61, 1437–1447.

Said, M., Elrakib, T.M., 2013. Enhancement of shear strength and ductility for reinforced concrete wide beams due to web reinforcement. HBRC J. (Housing and Building National Research Center) 9, 235–242.

Sapuan, S.M., Leenie, A., Harimi, M., Beng, Y.K., 2006. Mechanical properties of woven banana fibre reinforced epoxy composites. Mater. Des. 27, 689–693.

Satyanarayana, Kestur G., Arizaga Gregorio, G.C., Wypych, Fernando, 2009. Biodegradable composites based on lignocellulosic fibers – an overview. Progr. Polym. Sci. 34, 982–1021.

Sawpan, Moyeenuddin A., Pickering, Kim L., Fernyhough, Alan, 2011. Effect of various chemical treatments on the fibre structure and tensile properties of industrial hemp fibres. Composites: Part A 42, 888–895.

Singh Rajesh, Kumar, Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Ind. 9, 189–212.

Sreekumar, P.A., Thomas Selvin, P., Saiter Jean, Marc, Joseph, Kuruvilla, Unnikrishnan, G., Thomas, Sabu, 2009. Effect of fiber surface modification on the mechanical and water absorption characteristics of sisal/polyester composites fabricated by resin transfer molding. Composite A 40, 1777–1784.

Stocchi, Ariel, Lauke, Bernd, Vazquez, Analia, Bernal, Celina, 2007. A novel fiber treatment applied to woven jute fabric/vinyl ester laminates. Composite A 38, 1337–1343.

Summerscales, John, Dissanayake, Nilmini, Virk, Amandeep, Hall, Wayne, 2010. A review of bast fibres and their composites. Composite A 41, 1336–1344.

Textile biocomposites-net with link shodhganga.inflibnet.ac.in/bitstream/10603/509/12/12_part_3.pdf.

Venkateshwaran, N., Elayaperumal, A., Sathiya, G.K., 2012. Prediction of tensile properties of hybrid-natural fiber composites. Composite B 43, 793–796.

Vincent, Thomas, Ozbakkaloglu, Togay, 2013. Influence of concrete strength and confinement method on axial compressive behavior of FRP confined high- and ultra high-strength concrete. Composite B 50, 413–428.

Wang, Huanzi, Belarbi, Abdeldjelil, 2011. Ductility characteristics of fiber-reinforced-concrete beams reinforced with FRP rebars. Constr. Build. Mater. 25, 2391–2401.

Wang, Wei-Ming, Cai, Zai-Sheng, Yu, Jian-Yong, 2008. Study on the chemical modification process of jute fiber. J. Eng. Fibers Fabrics 3 (2).

Woven Fabric Engineering. Prof. Dr. Polona Dobnik Dubrovski (editor) Published by Sciyo.

Wu, G., 2002. Experimental Study and Theoretical Analysis on Strengthening Concrete Structures with FRP (Ph.D. thesis). Southeast University, Nanjing, China (in Chinese).

Wu, G., Luù, Z.T., Wu, Z.S., 2006. Strength and ductility of concrete cylinders confined with FRP composites. Constr. Build. Mater. 20 (3), 134–148.

Xiao, Y., Wu, H., 2000. Compressive behavior of concrete confined by carbon fiber composite jackets. J. Mater. Civil Eng. ASCE 12 (2), 139–146.

Xiao, Y., Wu, H., Concrete stub columns confined by various types of FRP jackets. In: Teng, J.G., (Ed.), Proceedings of the International Conference on FRP Composites in Civil Engineering, Hong Kong, China, 2001, 293–300.

Xu, Xun, Jayaraman, Krishnan, Morin, Caroline, Pecqueux, Nicolas, 2008. Life cycle assessment of wood-fibre-reinforced polypropylene composites. J. Mater. Process. Technol. 198, 168–177.

Zhang, Ming Qiu, Rong, Min Zhi, Lu, Xun, 2005. Fully biodegradable natural fiber composites from renewable resources: all-plant fiber composites. Compos. Sci. Technol. 65, 2514–2525.