Research Article

Sustainable approach towards utilizing Makrana marble waste for making water resistant green composite materials

Asokan Pappu[1,2] · Ranjan Chaturvedi[1,2] · Prashant Tyagi[1]

Received: 26 September 2019 / Accepted: 29 January 2020 / Published online: 6 February 2020

Abstract
During marble mining, processing, cutting and polishing, more than 12 MT (million tons) of marble waste is produced in the state of Rajasthan, India, which is now a major environmental issue. The marble waste used in the present study was collected from Makrana marble mining, Rajasthan. The major mineral present in marble waste were calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) and quartz (SiO_2). Composite materials were made using marble waste with epoxy resin. Textile fibres such as jute, cotton and glass fibres were used as reinforcing materials. The hybrid composites exhibited 54% better flexural strength (48.48 MPa) than the commercially available medium density fibre boards (24.23 MPa). Water absorption and thickness swelling values were less than 1% in green composites. The microstructural study of fractured surface of hybrid composite showed good interfacial bonding between the marble waste, fibre and the matrix. The findings of this study showed a promising outcome in introducing a new class of hybrid green composites to the composite industry and society for multifunctional applications, creating an avenue for circular economy with major environmental benefits.

Keywords Hybrid green composites · Marble waste · Waste valorisation · Jute fibre · Epoxy · Recycling

1 Introduction

Inorganic wastes generated during different industrial processes in abundance are of great concern leading to damage the natural resources, influence environment degradation and entangle global warming. About 16 MT of marble waste is generated annually in India and improper management of this industrial waste has led to environmental contamination at great extent. [1] New advancements in solid waste management have resulted in newer applications of these wastes such as alternative construction materials and substitute to traditional materials such as bricks, tiles, aggregates, ceramics, cement, and timber [2]. Marble powder also known as calcite tailing is a residual material resulting from the cutting and polishing of marble stone. In the recent years marble industries in many countries reached a new level of popularity and thus volume of marble waste powder and scrap produced has been increasing manifold annually. In last decades, researchers and manufacturers have shifted their focus from synthetic to natural fibre for use in making composite materials because of low cost and abundant availability in nature [3–5]. Usage of traditional synthetic fibres is now getting limited to few applications because of their hazardous nature and environmental point of view [6]. Marble waste has been used for many applications such as, geotechnical, building materials, chemical adjuvant for acid mine and reclamation [7], soil amendment to neutralize the acidic soil and soil treatment which in turn improved the yield of the hazelnut field [8, 9]. Marble stone slurry waste has been utilised as primary aggregate in concrete also marble sludge powder waste as a substitutes for natural sand in concrete [10, 11]. Marble waste has also been used to replace a part cement, to increase the compressive

✉ Asokan Pappu, asokanp3@yahoo.co.in | [1]CSIR- Advanced Materials and Processes Research Institute, Bhopal, M.P., India. [2]Academy of Scientific and Innovative Research, CSIR-AMPRI, Bhopal, M.P., India.

strength and also as an additive in composite cement production [12, 13]. Marble waste was used in making geopolymer based bricks which an increase in compressive strength and bulk density because of the improved interfacial adhesion [14]. In another research the waste pieces of marble was used as crushed stone instead of limestone in self-consolidating concrete (SCC) [15].

Marble waste has also been explored to produce composite products, using different type of matrix and fillers [16, 17]. The marble waste was processed and mixed in polymer matrix without any fibre reinforcements to make composite as artificial stones [18]. Artificial stones were made with density close to marble and some properties better than the marble [19]. Marble waste was used with fibre reinforcement to make hybrid composites with about 31% better flexural strength [20]. From literature survey it has been found that in last 10 years significant research has been done in countries like Italy, Turkey and Brazil. Work done so far use of marble waste for making polymer matrix composite using various techniques like, compression moulding, vacuum bagging, and vacuum vibro compression for the high density composites [19]. In a research work, recycled PET and marble waste was used to make composite using extrusion system followed by injection moulding, which showed good mechanical properties [21]. Micromarble particles along with glass fibre were used to make composite tiles using recycled PET as the binder matrix [22]. Mechanical property of composite with high marble waste contents (60–80%) and with different polymer system (Epoxy/PE) was evaluated and it was found that composites with PE and marble waste showed better flexural property than composites with epoxy and marble waste [16].

Marble waste production has also been increased in India in recent years mainly in state of Rajasthan. Many hectares of land have been occupied for disposal and storage of waste marble slurry which now became a serious problem in this State. Literature survey revealed that in India, as compared to world scenario, less research have been done for the utilization of marble waste slurry. In a study, granite and marble waste was mixed with epoxy resin along with glass fibre to make high performance composite [23]. In another study, along with jute fibre mat and epoxy resin Rajasthan marble waste was used in varying weight percentage to make composites [24]. Marble waste has utilization potential in the area of bricks, concrete and wood substitute composite materials. Potential usage of marble slurry waste along with natural jute fibre for making door shutters has also been explored [25].

The aim of this study is to characterize the marble waste collected from the marble slurry dumping sites in Makrana, Rajasthan and to produce a new class of composite materials from marble waste. The impact of various natural and synthetic fibres along with the marble waste particulates was studied in making the hybrid green composite materials.

2 Materials and methods

2.1 Materials

The marble waste used in the present study was collected from marble waste slurry dumping sites in Makrana, Rajasthan, India. The commercially available jute textile fibre, cotton textile fibre and glass textile fibre were used in this study as a reinforcement materials for making composites. Epoxy resin (Lapox B-11) having epoxy value 5.25–5.45 and specific gravity 1.16 was used. Hardener (K-48) in combination with epoxy having pot life 20 min was used as a matrix material in composites sample.

2.2 Sample preparation

The marble waste was first ground to get uniformity in particle size, further dried in oven at 70 °C for 72 h. The Epoxy and Hardener were used in the ratio of 10:1 for the preparation of composites and different specimens were casted in a mould size of 30 cm × 30 cm incorporating with various natural and synthetic fibres (jute, cotton and glass) with the addition of treated marble waste, under compression moulding system at 120 ± 5 °C at a pressure 45 psi for 10 min followed by curing at 36 ± 2 °C for 8 h. Schematic diagram of sample preperation is shown in Fig. 1. The percentage of the marble waste in all composite specimens were kept 60% by weight, which was decided based on the initial experiments.

2.3 Testing

X-ray diffraction was done using Rigaku (Japan) Miniflex-II desktop X-ray Diffractometer. Thermogravimetric analysis was done using Metler Toledo (USA) TGA/DSC-1 star system. For determination of conductivity and pH of the marble waste LABMAN (India) Conductivity meter LMCM-20 and LABMAN pH meter 5 point calibration LMPH-12 were used respectively. For particle size analysis Horiba LA95052 particle size distribution analyser was used. For the evaluation of tensile properties, samples were prepared according to the ASTM D638-14 and the test was conducted on Instron (USA) 8800 universal testing machine (UTM). For the determination of the flexural properties of the composites the three point bend samples were prepared according to the ASTM D790-17 and test was done on Lloyd Instrument (UK) LRX Plus UTM. The breaking force and extension at maximum load of the fabric used in this study was calculated according to ASTM

5053-11 using Lloyd Instrument (UK) LRX Plus UTM. The 24 h water absorption test of the polymer composites was determined in accordance with the ASTM D 570-8 and the thickness swelling was also calculated from rectangular strips immersed in deionized water for 24 h at the room temperature.

3 Results and discussion

3.1 Marble waste

3.1.1 X-ray diffraction

Figure 2 shows XRD pattern of the marble waste collected from Makrana district of Rajasthan, it was observed that (Fig. 2) marble waste has three major minerals namely calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) and quartz (SiO_2). Based on their relative intensity, it was confirmed that dolomite concentration in this sample is slightly high as compared to calcite and quartz. The mineralogical studies of marble waste sample showed dolomite as major mineral which might be reason for higher bulk density as compared to the reported value in the previous work [26].

3.1.2 Thermogravimetric analysis

From the obtained TGA data illustrated in Fig. 2, this marble sample collected from Markrna, Rajasthan showed similar thermal profile as that of a typical pure calcium carbonate. The samples underwent water loss around 100–110 °C followed by a high decomposition, reaching approximately 42% between 695 and 799 °C. A smooth and steady decomposition was observed with a well-defined inflection point.

3.1.3 Physical properties

The bulk density of the samples was found to be 1.49 g/cc while specific gravity was 2.59 of the collected marble waste. The porosity was 43.52. Mean particle size of the marble waste was 65.8 µm with D_{10} and D_{90} values 29.56 µm and 101.53 µm respectively. Electrical conductivity was 0.30 mS/cm and pH of the marble waste was 7.83 which indicates the equal concentration of hydroxide and hydrogen ions in the sample. A previous work [13] reported almost similar value of specific gravity (2.60) while another work [27] showed slightly higher value of specific gravity (2.62–2.72). The higher value of porosity indicates the presence of more degree of saturation and void ratio. The work done by [28] showed highly alkaline pH which indicates that the sample was fresh and less exposed to environment. The research done by [29] showed electrical conductivity of 2.20 mS/cm which is higher than present work. The value of electrical conductivity is directly proportional to the concentration of anions or cations in the sample degree of weathering in natural weathering.

3.1.4 FTIR analysis

The FTIR spectrum of marble waste collected from Makrana is presented in Fig. 3. It was observed that

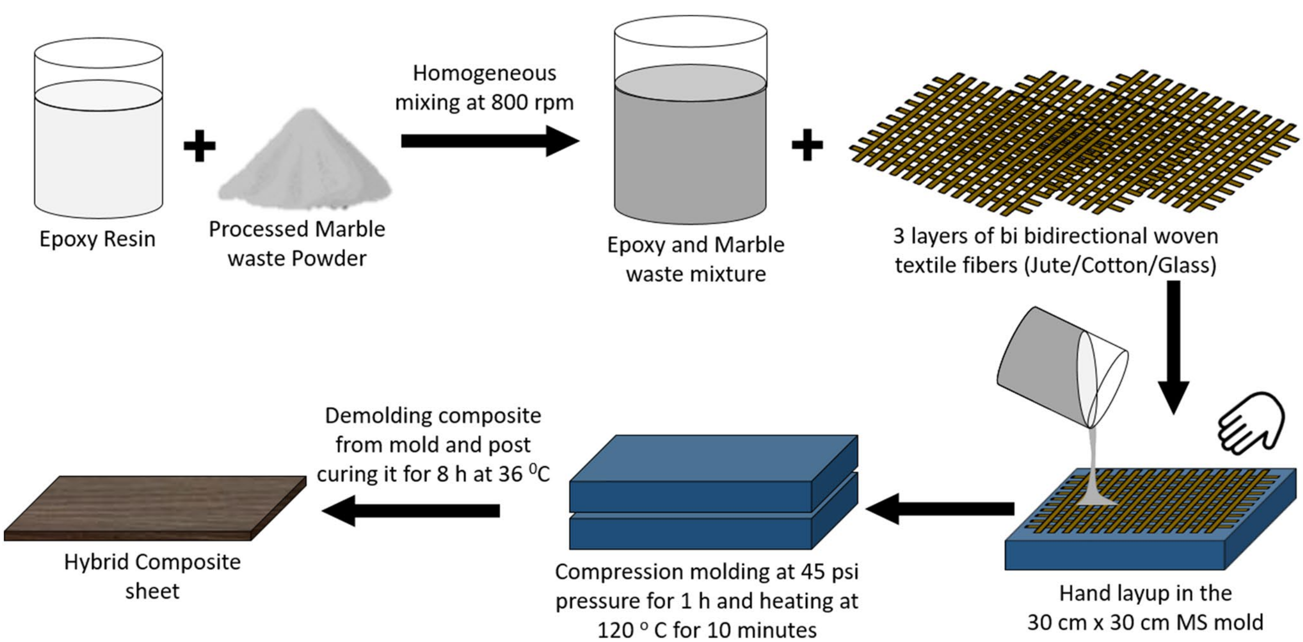

Fig. 1 Schematic diagram of sample preparation

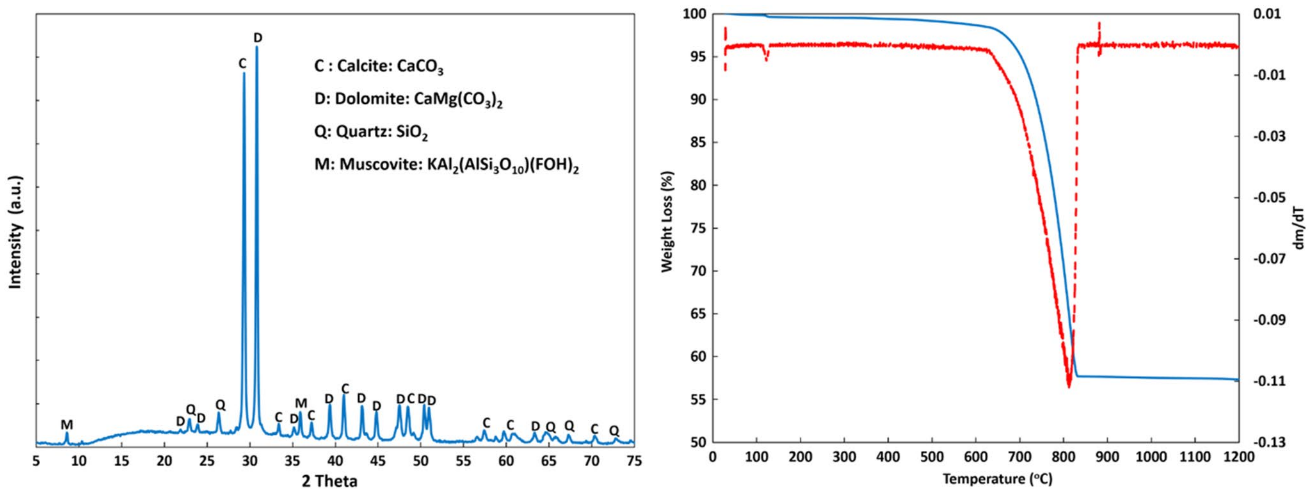

Fig. 2 XRD analysis and TGA analysis of Makrana marble sample

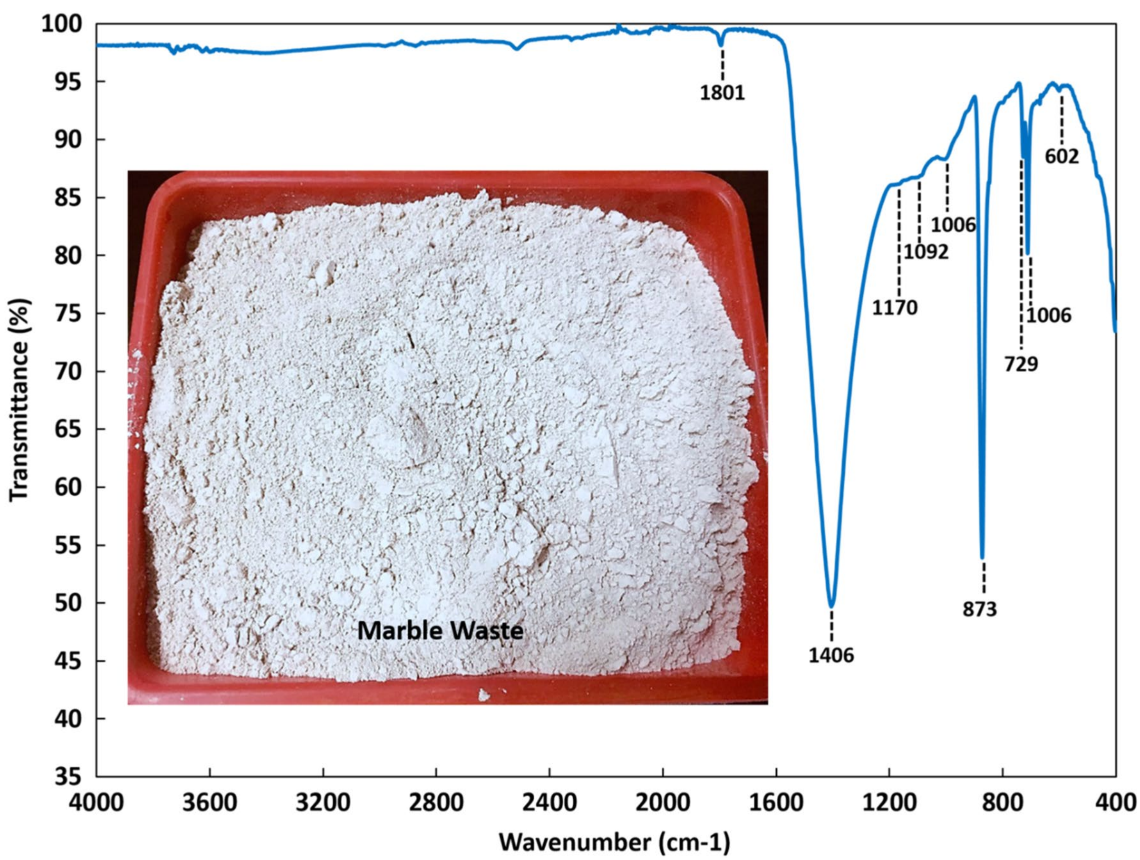

Fig. 3 FT-IR spectra of the marble waste (marble waste insert)

absorption band of carbonate dominate the spectrum as reported in other works [30, 31]. The absorption band at 1092 cm^{-1} can be attributed to symmetric stretching of carbonate group. The sharp bands at 873 cm^{-1} and 712 cm^{-1} arose due to out-of-plane bending and in-plane bending respectively. The strong and large band observed at 1406 cm^{-1} is due to asymmetric stretching of carbonate. A small band observation detected at 1801 cm^{-1} can be further attributed to a combination of both symmetric stretching and in-plane bending.

3.2 Composites

3.2.1 Tensile properties

In the present study, composites made with jute fibres showed a tensile strength of 20.59 ± 1.56 MPa with the maximum strain of 0.78% (Fig. 4) and tensile modulus was 4.42 ± 0.61 GPa which is lower than composite with only marble waste (6.27 ± 1.06 GPa). It is reported that lower marble waste content (30%) and jute fibre as reinforcement 75% increase in tensile strength was achieved [24]. In the present study, the composite with cotton textile fabric reinforcement showed a tensile strength of 9.90 ± 2.64 MPa (Fig. 5). Cotton fiber reinforced composite showed modulus of elasticity of 4.20 ± 0.48 GPa which is almost similar to that of composite with jute fibres. In previous reported work, composites with recycled PET and marble waste showed a tensile strength of 16 MPa [21]. In the present study, the composites with glass fibres showed a tensile strength of 89.40 ± 4.29 MPa and tensile modulus of 5.21 ± 0.54 GPa (Fig. 6). The strain obtained in this case was 4.2% which is higher than all other composites. In a previous research work, lower granite waste content (20%) and higher glass fibre content (40%) was used and tensile strength of 269 MPa was obtained [23]. The composite with only marble waste showed a tensile strength of 12.85 ± 2.36 MPa (Fig. 7) and maximum strain of 0.32%. Characteristics such as weight (GSM), breaking strength and elongation at break of jute, cotton and glass textile fabric are shown in Table 1.

3.2.2 Flexural properties

The jute based composites showed flexural strength of 48.48 ± 3.66 MPa (Fig. 8) which was similar to the composites with only marble waste. The corresponding modulus value was 6.31 ± 0.21 GPa and maximum strain was 1.38%. In comparison, flexural strength of 71.87 MPa was achieved in a previous study by using half the filler content and higher jute fibre weight content (40%) in epoxy based composites [24]. The cotton fibre composites showed the flexural strength of 37.20 ± 2.01 MPa and flexural modulus

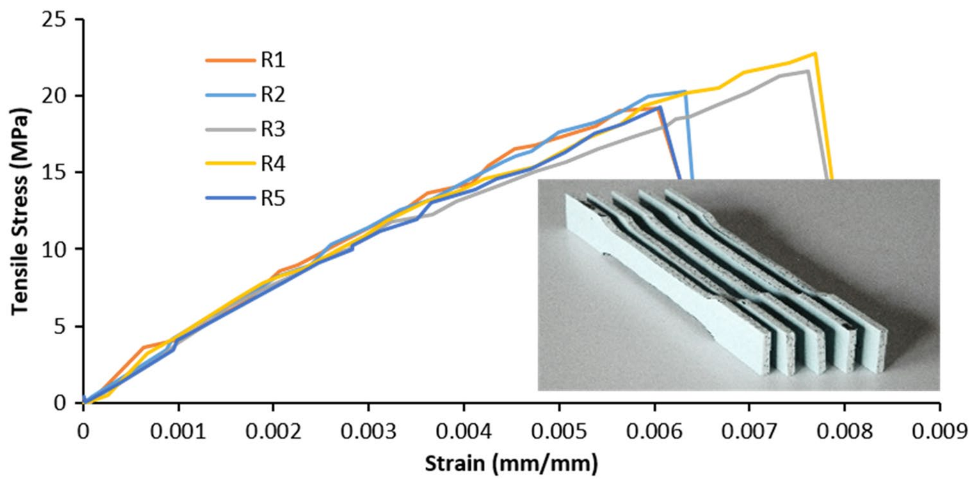

Fig. 4 Tensile test results of the EPC-J composite sample

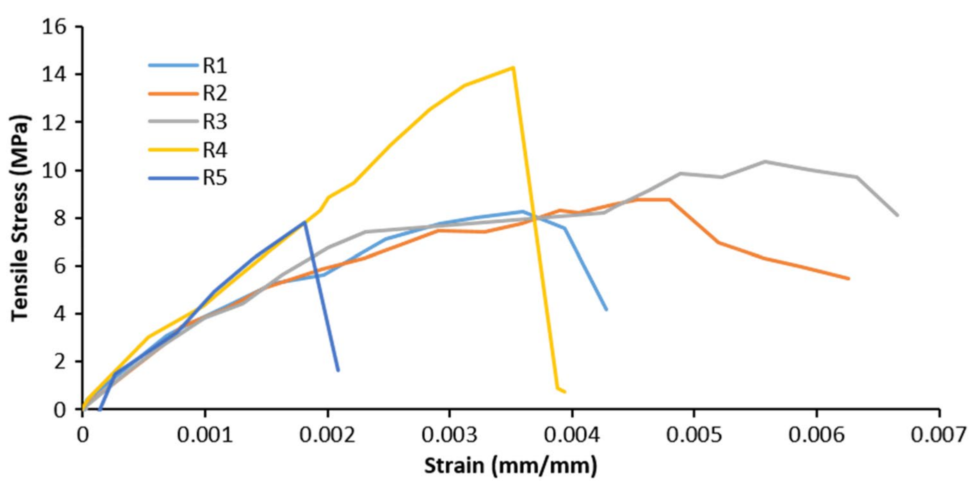

Fig. 5 Tensile test results of the EPC-C composite sample

Fig. 6 Tensile test results of the EPC-G composite sample

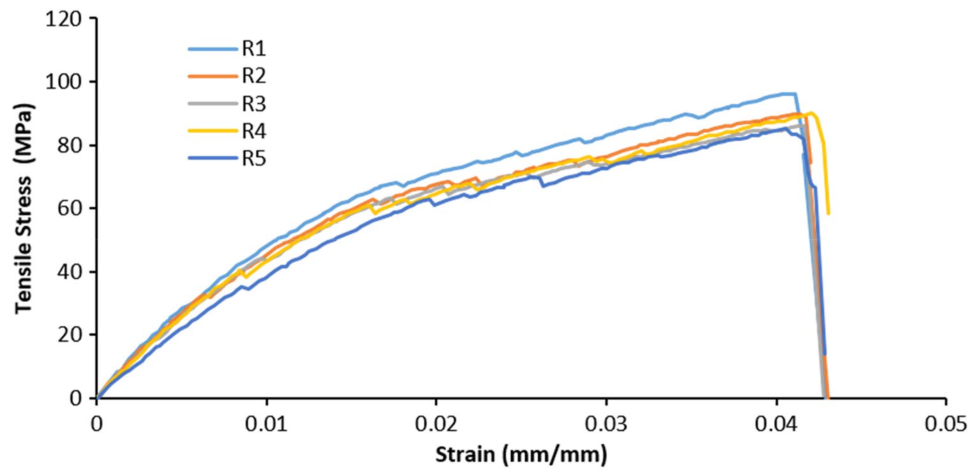

Fig. 7 Tensile test results of the EPC-MW composite sample

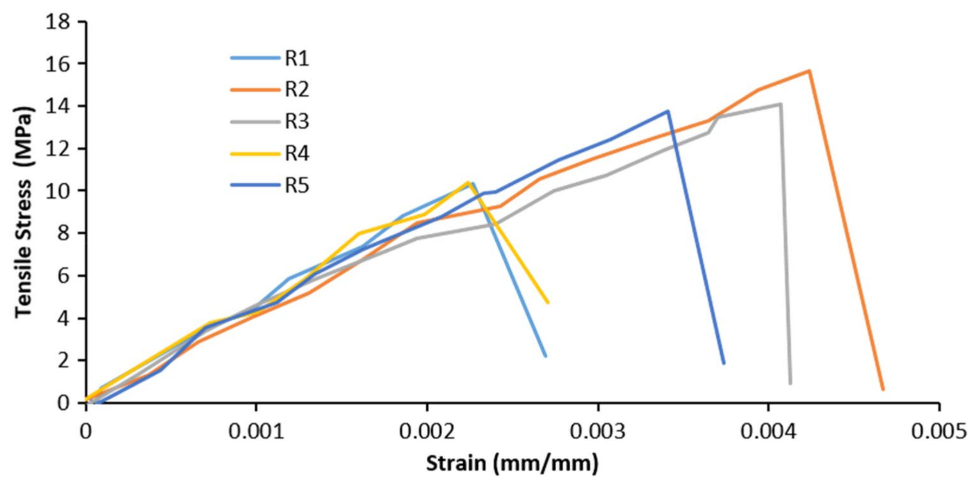

Table 1 Breaking strength and elongation

Textile fibres	Sample ID	Maximum Load (N)	Extension at Max. Load (mm)	Weight (GSM)
Cotton	C1	66.22	11.17	46.3
	C1	52.62	9.81	49.2
	C3	68.92	11.40	45.8
	Mean	62.59	10.79	47.1
	SD	8.74	0.86	1.8
Jute	J1	249.83	3.53	241.9
	J1	187.53	4.40	250.1
	J3	201.72	4.07	242.1
	Mean	213.03	4.00	244.7
	SD	32.65	0.44	4.7
Glass	G1	909.02	5.42	371.3
	G2	832.28	7.00	362.4
	G3	829.38	4.12	364.9
	Mean	856.89	5.51	366.2
	SD	45.17	1.44	4.6

of 7.50 ± 0.26 GPa (Fig. 9). The flexural strength was minimum in the case of cotton fibres as compared to all other composites. Strain was also minimum as compared to all other composites with a value of 0.6%. A previous study reported a flexural strength of 22.2 MPa with similar marble waste and resin content without any fibre reinforcement [16]. In the present study, composites with the glass fibre showed the flexural strength 136.04 ± 12.96 MPa and the flexural modulus of 7.51 ± 0.52 GPa (Fig. 10). The strain was also 3.5% which is higher than all other composites. Another work [23] reported that even with much lower filler content (20%) and high weight proportion of glass fibre (40%), 316 MPa flexural strength was obtained. Composite with only marble waste and epoxy showed a flexural strength of 48.05 ± 1.19 MPa and the flexural modulus of 7.12 ± 0.43 GPa, the strain was only 0.8% (Fig. 11). Pine cone dust and ATH [32] resulted in flexural strength of 51.36 MPa. Flexural strength of 22.2 MPa was achieved with similar marble waste content [16]. Graphical

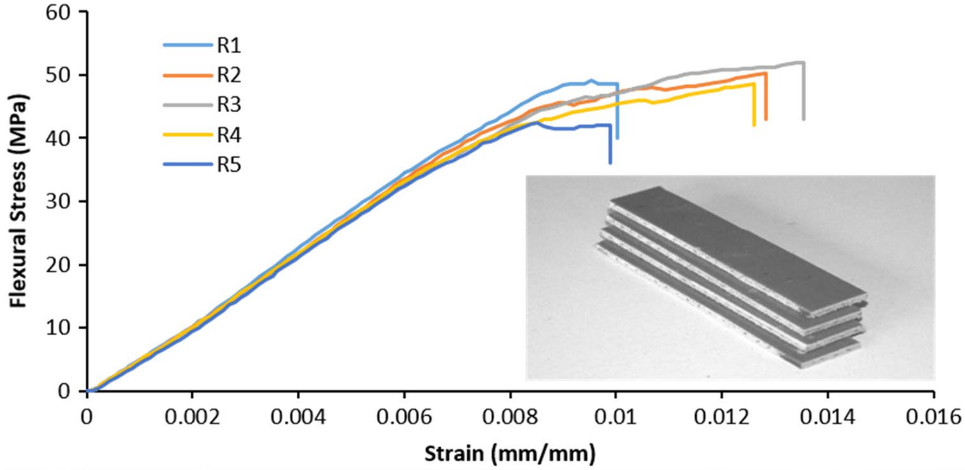

Fig. 8 Three point bending test results of the EPC-J composite sample

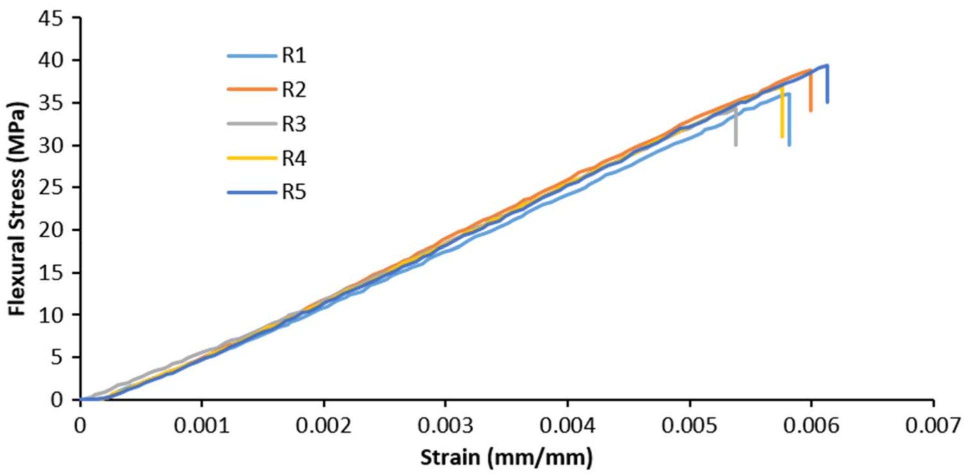

Fig. 9 Three point bending test results of the EPC-C composite sample

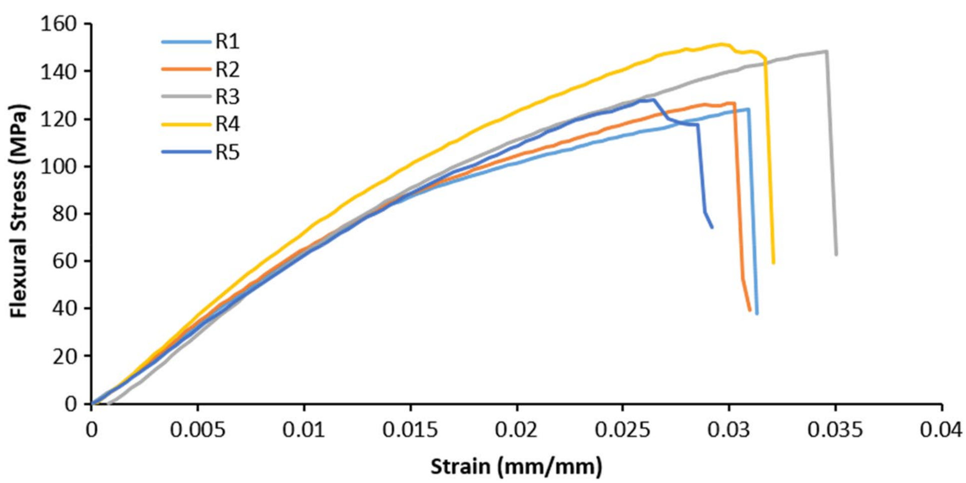

Fig. 10 Three point bending test results of the EPC-G composite sample

comparison of tensile modulus and flexural modulus of all the prepared composites is ahown in Fig. 12.

Overall, all the hybrid green composite materials showed superior flexural and tensile modulus values than the convention wood products like MDF, PB and Ply wood. The teak wood showed a closer value of flexural and tensile values to Hybrid Green Composite (Table 2).

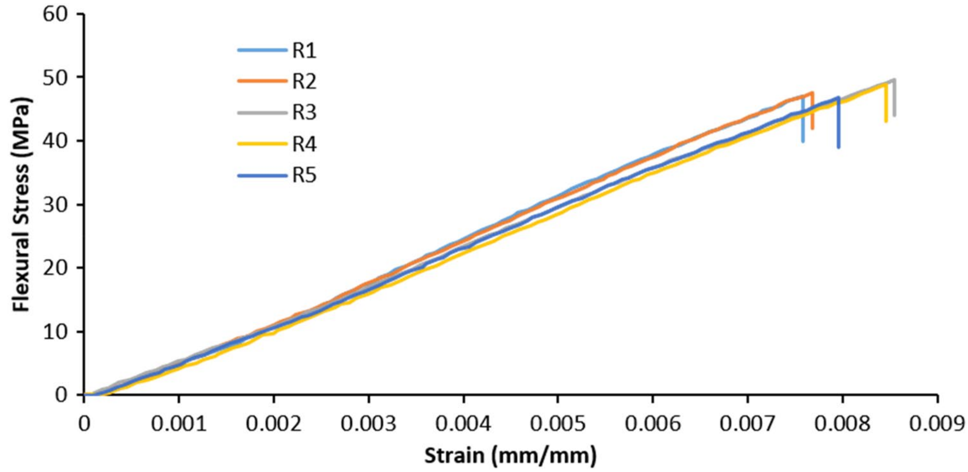

Fig. 11 Three point bending test results of the EPC-MW composite sample

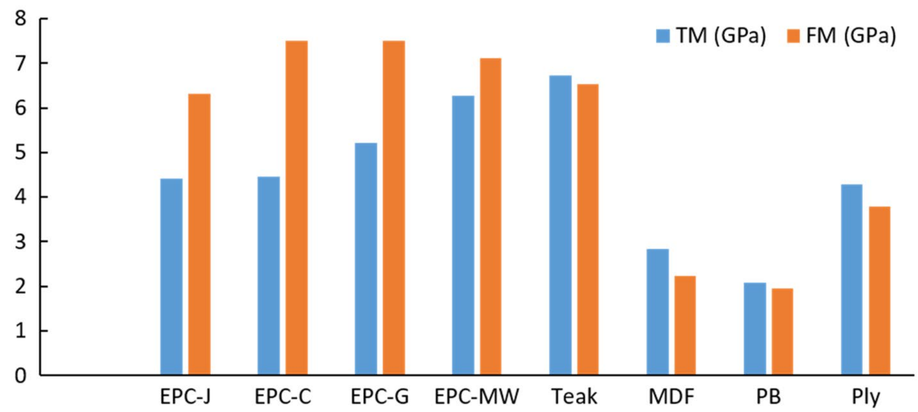

Fig. 12 Comparison of tensile modulus (TM) and flexural modulus (FM) of the composite samples with commercial products

Table 2 Comparison of mechanical and physical properties of materials

S. no	Material	TS (MPa)	TM (GPa)	FS (MPa)	FM (GPa)	WA (%)	ThS (%)	ρ (g/cm^3)
1	EPC-MW	12.85	6.27	48.05	7.12	0.09	2.02	1.565
2	EPC-Jute	20.59	4.42	48.48	6.31	0.56	0.00	1.557
3	EPC-Cotton	9.90	4.45	37.20	7.50	0.15	0.00	1.630
4	EPC-Glass	89.4	5.21	136.04	7.51	0.53	0.65	1.687
5	Teak	57.47	6.73	65.99	6.53	48.02	–	0.521
6	MDF[a]	13.33	2.84	24.23	2.23	87.74	18.42	0.694
7	PB[a]	20.80	2.08	16.15	1.95	43.37	30.39	0.652
8	Ply[a]	54.02	4.29	57.19	3.78	62.87	9.96	0.525
9	Tipwood®	80.00	–	70.00	6.00	1.20	–	1.150
10	MDF Grade –I	–	2.8	28	–	30	4	0.6–0.9
11	HD PB BWR Grade	34.32	–	44.13	–	10	–	0.9–1.2
12	Plywood BWR Grade	–	4.5	36	–	–	–	–

TS tensile strength, *TM* tensile modulus, *FS* flexural strength, *FM* flexural modulus, *WA* water absorption, *ThS* thickness swelling, *ρ* density; [a]Tested at CSIR-AMPRI

3.2.3 Water absorption and thickness swelling

The density of the marble waste composites with different fibres varied between 1.5–1.7 g/cm^3 while the other conventional wood products varied between 0.52–0.69 g/cm^3 (Fig. 13). The increase in the density of these composites is due to the high bulk density of marble waste which is 1.49 ± 0.002 g/cm^3. The water absorption of composites was higher with the jute fabric (0.562 ± 0.015%) as compared to due to presence of large number of –OH group

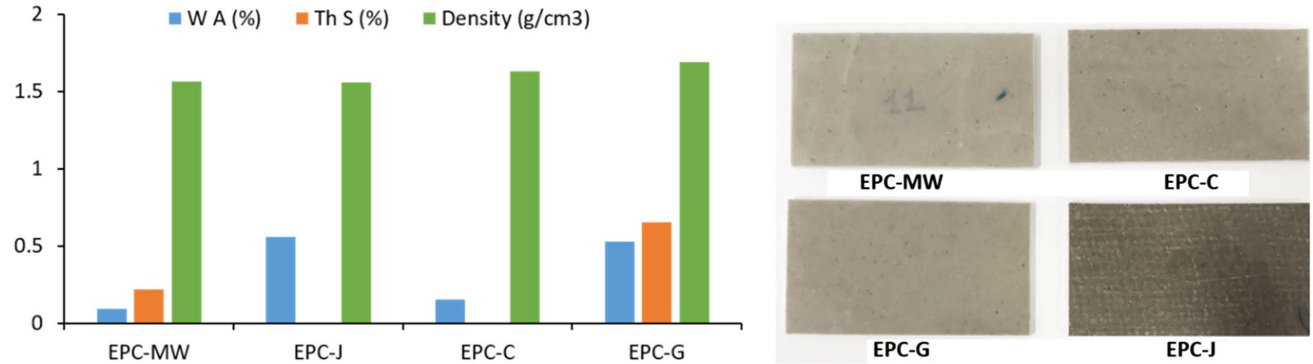

Fig. 13 Comparison of density, water absorption (WA) and thickness swelling (Th S)

in jute (cellulosic). The present study revealed that there is negligible thickness swelling in the composites which indicates that there no swelling or shrinkage in the material which is considered an important parameter for practical applications. Though most previous studies don't mention thickness swelling property but in one case [16] the thickness swelling was almost similar to the one reported in present study. Mechanical and Physical properties of the composite materials along with their repetition, mean values and standard deviation values are given in Table 3.

Table 3 All properties hybrid composites

S. no.	Sample ID		TS (MPa)	TM (GPa)	FS (MPa)	FM (GPa)	ρ (g/cm^3)	WA (%)	ThS (%)
1	EPC-Jute	R-1	19.15	4.50	49.10	6.62	1.684	0.546	0.000
		R-2	20.23	4.07	50.35	6.39	1.581	0.565	0.000
		R-3	21.61	4.50	52.01	6.12	1.406	0.575	0.000
		R-4	22.75	5.33	48.54	6.31	–	–	–
		R-5	19.22	3.71	42.38	6.10	–	–	–
	Mean		20.59	4.42	48.48	6.31	1.557	0.562	0.000
	SD		1.56	0.61	3.66	0.21	0.115	0.015	0.000
2	EPC-Glass	R-1	96.03	5.76	124.15	7.39	1.549	0.137	0.666
		R-2	89.85	5.46	127.04	7.53	1.761	0.165	0.662
		R-3	85.92	5.24	148.45	7.54	1.752	0.158	0.622
		R-4	89.93	5.25	151.67	8.26	–	–	–
		R-5	85.26	4.32	128.91	6.81	–	–	–
	Mean		89.40	5.21	136.04	7.51	1.687	0.153	0.650
	SD		4.29	0.54	12.96	0.52	0.098	0.015	0.024
3	EPC-Cotton	R-1	8.25	4.11	36.16	7.14	1.558	0.156	0.000
		R-2	8.77	5.07	38.90	7.82	1.583	0.173	0.000
		R-3	10.37	4.01	34.59	7.35	1.749	0.142	0.000
		R-4	14.29	4.86	36.87	7.63	–	–	–
		R-5	7.8	4.2	39.48	7.56	–	–	–
	Mean		9.90	4.45	37.20	7.50	1.630	0.157	0.000
	SD		2.64	0.48	2.01	0.26	0.085	0.016	0.000
4	EPC-MW	R-1	13.75	7.84	47.24	7.44	1.442	0.097	2.075
		R-2	10.36	5.96	47.55	7.70	1.707	0.090	2.007
		R-3	15.67	5.56	49.67	6.90	1.546	0.092	1.977
		R-4	14.07	5.2	48.91	6.69	–	–	–
		R-5	10.42	6.81	46.87	6.89	–	–	–
	Mean		12.85	6.27	48.05	7.12	1.565	0.093	2.020
	SD		2.36	1.06	1.19	0.43	0.109	0.004	0.050

TS tensile strength, *TM* tensile modulus, *FS* flexural strength, *FM* flexural modulus, *WA* water absorption, *Th.S* thickness swelling, *ρ* density

3.2.4 Microstructural analysis

Microstructure of the fractured surface of the composites were studied under FE-SEM. Figure 14a shows bonded marble waste particle with the jute fibres indicating that the epoxy resin is binding the particles and fibres leading to an effective stress transfer. Figure 14d shows ruptured jute fibres which is further indication of good bonding between matrix and fibres. In Fig. 14b there was no void observed between the fibre and the matrix indicating proper wetting of fibres in matrix. Some pores were also observed which can be attributed to the air bubbles trapped in matrix during the high viscous mixing of resin. Air voids/pores results in inefficient adhesion and also act as stress concentration points and thus are the reason for lesser strength of composite materials [33].

3.2.5 FTIR analysis

Fourier transform infrared spectroscopy of all the composite samples was performed. The FT-IR spectra of the four epoxy composites are presented in the Fig. 15. Since ATR technique characterize only the surface, it is not possible to identify band appearing due to Jute, Glass and Cotton fibres embedded within the matrix. Nevertheless, following bands emanating from epoxy can be assigned that are common in all spectra [34] [35]. Band at 3320–2270 cm^{-1} represents O–H stretching

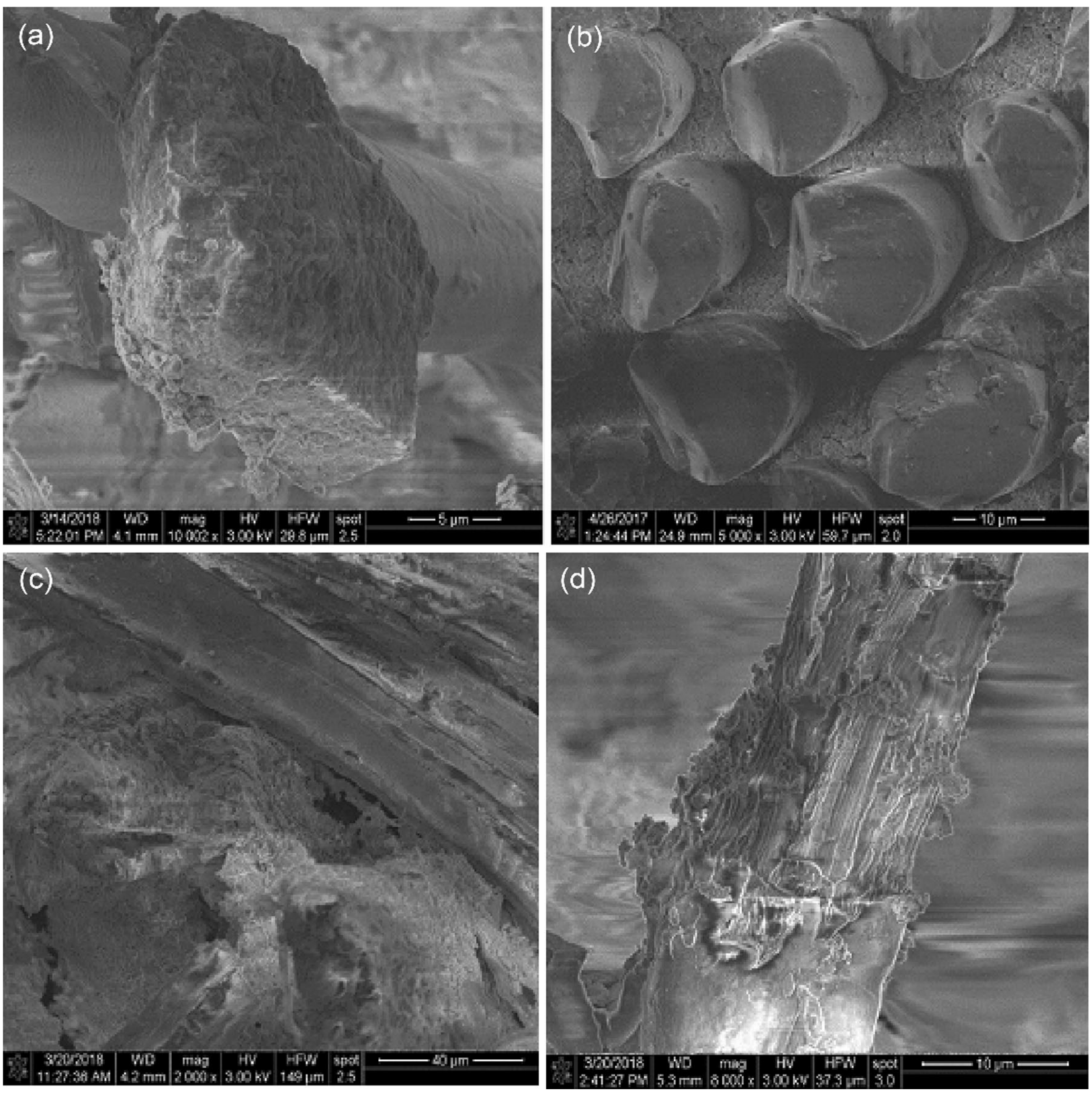

Fig. 14 Microstructure of hybrid composites

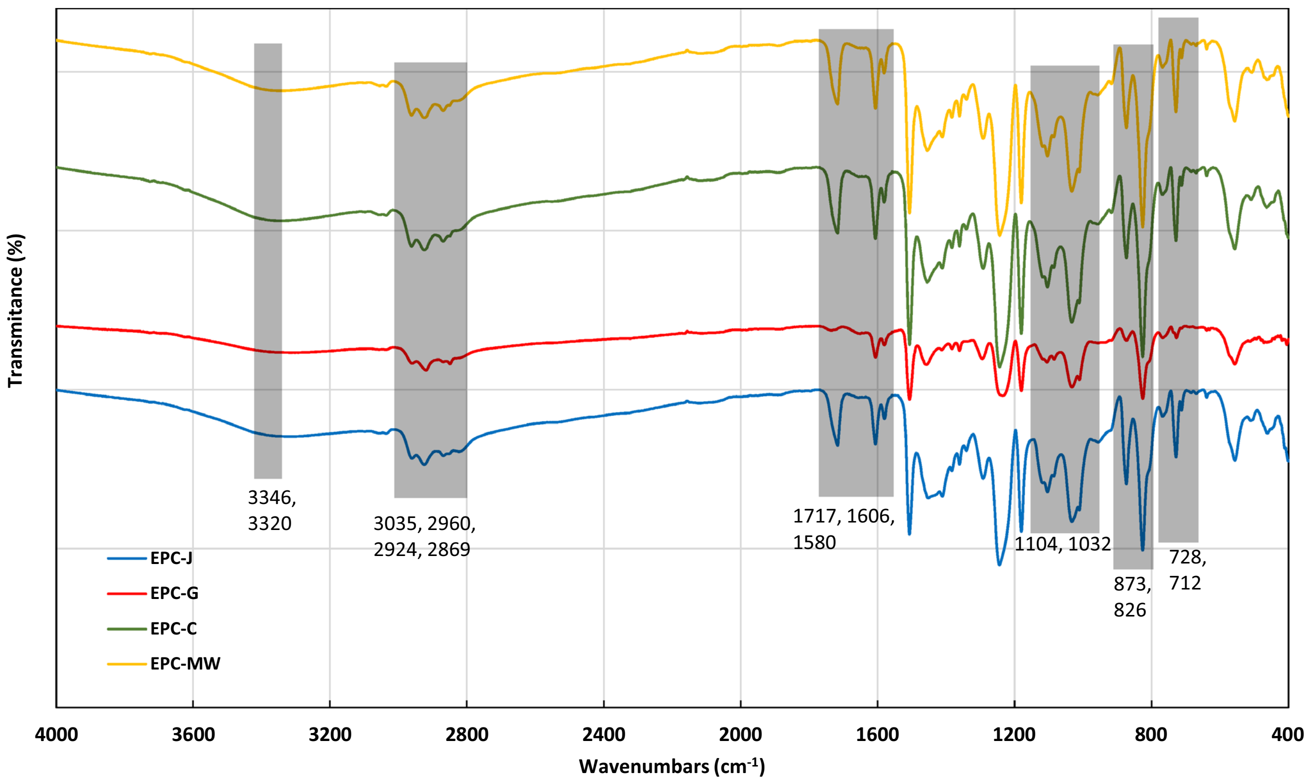

Fig. 15 FT-IR spectra of cross-sections of composite samples

while bands at 3062–3036 cm^{-1} represents stretching of C–H of oxirane ring. 2961–2865 cm^{-1} bands represent stretching of C–H and CH aromatic and aliphatic. The band appearing at 1717 cm^{-1} represents stretching in C=O bond was observed to be weakest in case of glass fibre composites. 1606–1581 cm^{-1} is the stretching in C=C aromatic ring from epoxy. 1507 cm^{-1} is the stretching in C–C of aromatic ring from epoxy. Bands at 1032–1104 cm^{-1} represents the stretching in C–O–C of ethers and were of weakest intensity in case of glass fibres composites. 873 cm^{-1} represents out of plane bending of carbonate group from marble 826 cm^{-1} represent the stretching C–O–C of oxirane group. 768 cm^{-1} represent rocking CH_2 group.

4 Conclusions

In this study, calcite and dolomite rich marble waste was used as a filler with different natural and synthetic textile fibres as reinforcement materials in epoxy resin medium to make hybrid green composites. The manufactured composites with jute fibre exhibited tensile strength of 20.59 ± 1.56 MPa, flexural strength of 48.48 ± 3.66 MPa, water absorption of 0.56 ± 0.015% and no dimensional change. Glass fibre reinforced marble waste composites showed tensile strength of 89.4 ± 4.29 MPa, flexural strength of 136.04 ± 12.96 MPa. The performance of the composite reveals that there is great scope for application of this hybrid composites in building materials and furniture industries. The consumption of marble waste in large amounts (more than 60% by wt.) in these composites will lead to sustainable recycling and management of marble waste in converting it into highly durable and sustainable green composites. Further the use of jute fibres will increase the biodegradability and recyclability quotient of the composites while promoting a sustainable materials strategy.

Acknowledgements Authors are thankful to Department of Science and Technology, Ministry of Science and Technology, Government of India for funding this project work. Authors are also thankful to Dr. A. K. Srivastava, Director, CSIR-AMPRI, Bhopal for the support in carrying out this research work. Authors are also thankful to Dr. Edward Peters and Dr. Alka Mishra for their assistance.

Funding Funding was provided by Department of Science and Technology, Government of India (Grant No. DST/TSG/WM/2015/487/G).

Compliance with ethical standards

Conflict of interest The authors declares no conflict of interest.

References

1. Pappu A, Thakur VK (2017) Towards sustainable micro and nano composites from fly ash and natural fibers for multifunctional applications. Vacuum 146:375–385
2. Asokan P, Saxena M, Asolekar SR (2005) Coal combustion residues—Environmental implications and recycling potentials. Resour Conserv Recycl 43(3):239–262
3. Pappu A, Patil V, Jain S, Mahindrakar A, Haque R, Thakur VK (2015) Advances in industrial prospective of cellulosic macromolecules enriched banana biofibre resources: a review. Int J Biol Macromol 79:449–458
4. Bajpai PK, Singh I, Madaan J (2012) Comparative studies of mechanical and morphological properties of polylactic acid and polypropylene based natural fiber composites. J Reinf Plast Compos 31(24):1712–1724
5. Singh AA, Palsule S (2014) Thermal properties of jute fiber reinforced chemically functionalized high density polyethylene (JF/CF-HDPE) composites developed by palsule process. Appl Polm Compos 2(2):97–108
6. Pappu A, Saxena M, Thakur VK, Sharma A, Haque R (2016) Facile extraction, processing and characterization of biorenewable sisal fibers for multifunctional applications. J Macromol Sci Part A Pure Appl Chem 53(7):424–432
7. Barros RJ, Jesus C, Martins M, Costa MC (2009) Marble stone processing powder residue as chemical adjuvant for the biologic treatment of acid mine drainage. Process Biochem 44(4):477–480
8. Tozsin G, Arol AI, Oztas T, Kalkan E (2014) Using marble wastes as a soil amendment for acidic soil neutralization. J Environ Manag 133:374–377
9. Tozsin G, Oztas T, Arol AI, Kalkan E, Duyar O (2014) The effects of marble wastes on soil properties and hazelnut yield. J Clean Prod 81:146–149
10. André A, De Brito J, Rosa A, Pedro D (2014) Durability performance of concrete incorporating coarse aggregates from marble industry waste. J Clean Prod 65:389–396
11. Hameed MS, Sekar ASS (2009) Properties of green concrete containing quarry rock dust and marble sludge powder as fine aggregate. J Eng Appl Sci 4(4):83–89
12. Singh R, Bhutani M, Syal T (2015) Strength evaluation of concrete using marble powder and waste crushed tile aggregates. Int J Sci Emerg Technol Latest Trends 20(1):18–28
13. Aruntaş HY, Gürü M, Dayi M, Tekin I (2010) Utilization of waste marble dust as an additive in cement production. Mater Des 31(8):4039–4042
14. Thakur AK, Pappu A, Thakur VK (2019) Synthesis and characterization of new class of geopolymer hybrid composite materials from industrial wastes. J Clean Prod 230:11–20
15. Uygunoɀlu T, Topçu IB, Çelik AG (2014) Use of waste marble and recycled aggregates in self-compacting concrete for environmental sustainability. J Clean Prod 84(1):691–700
16. Borsellino C, Calabrese L, Di Bella G (2009) Effects of powder concentration and type of resin on the performance of marble composite structures. Constr Build Mater 23(5):1915–1921
17. Saxena M, Morchhale RK, Asokan P, Prasad BK (2008) Plant fiber—industrial waste reinforced polymer composites as a potential wood substitute material. J Compos Mater 42(4):367–384
18. Gomes Ribeiro CE, Sanchez Rodriguez RJ, Carvalho EAD (2017) Microstructure and mechanical properties of artificial marble. Constr Build Mater 149:149–155
19. Souza F, Eduardo C, Ribeiro G, Jesus R, Rodriguez S (2017) Physical and mechanical characterization of artificial stone with marble calcite waste and epoxy resin. Mater Res 21(1):1–6
20. Borazan AA, Gokdai D (2017) Polymer composites reinforced with waste marble dust and fibers from chicken feathers as an alternative material. Fresenius Environ Bull 26(3):2095–2103
21. Çınar ME, Kar F (2018) Characterization of composite produced from waste PET and marble dust. Constr Build Mater 163:734–741
22. Icduygu MG, Aktas L, Altan MC (2012) Characterization of composite tiles fabricated from poly(ethylene terephthalate) and micromarble particles reinforced by glass fiber mats. Polym Compos 33(11):1921–1932
23. Rout AK, Satapathy A (2015) Study on mechanical and erosion wear performance of granite filled glass-epoxy hybrid composites. Proc Inst Mech Eng Part L J Mater Des Appl 229(1):38–50
24. Sharma A, Patnaik A (2018) Experimental investigation on mechanical and thermal properties of marble dust particulate-filled needle-punched nonwoven jute fiber/epoxy composite. JOM 70(7):1–5
25. Saxena M, Mehrotra P, Pappu A (2010) Innovative building materials developed from natural fibres and industrial waste. Land Contam Reclam 18(January):355–363
26. Rajgor MB, Patel NC, Pitroda J (2013) A study on marble waste management: opportunities and challenges in current age for making value added bricks. In: Proceedings of national conference CRDCE13, pp 20–21
27. Ercikdi B, Külekci G, Yılmaz T (2015) Utilization of granulated marble wastes and waste bricks as mineral admixture in cemented paste backfill of sulphide-rich tailings. Constr Build Mater 93:573–583
28. Fernández-Caliani JC, Barba-Brioso C (2010) Metal immobilization in hazardous contaminated minesoils after marble slurry waste application. A field assessment at the Tharsis mining district (Spain). J Hazard Mater 181(1–3):817–826
29. Moreno-Barriga F, Díaz V, Acosta JA, Muñoz MÁ, Faz Á, Zornoza R (2017) Organic matter dynamics, soil aggregation and microbial biomass and activity in Technosols created with metalliferous mine residues, biochar and marble waste. Geoderma 301:19–29
30. Toschi F et al (2013) A multi-technique approach for the characterization of Roman mural paintings. Appl Surf Sci 284:291–296
31. Şahbaz DA, Acikgoz C (2017) Cross-linked chitosan/marble powder composites for the adsorption of Dimozol Blue. Water Sci Technol 76(10):2776–2784
32. Gokdai D, Borazan AA, Acikbas G (2017) Effect of marble: pine cone waste ratios on mechanical properties of polyester matrix composites. Waste Biomass Valoriz 8(5):1855–1862
33. Silva FS, Gomes Ribeiro CE, Sánchez Rodriguez RJ (2018) Physical and mechanical characterization of artificial stone with marble calcite waste and epoxy resin. Mater Res. https://doi.org/10.1590/1980-5373-mr-2016-0377
34. Nikolic G, Zlatkovic S, Cakic M, Cakic S, Lacnjevac C, Rajic Z (2010) Fast Fourier transform IR characterization of epoxy GY systems crosslinked with aliphatic and cycloaliphatic EH polyamine adducts. Sensors 10(1):684–696
35. Canavate J, Colom X, Pages P, Carrasco F (2000) Study of the curing process of an epoxy resin by FTIR Spectroscopy. Polym Plast Technol Eng 39(5):937–943