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Recent Advances on Fly ash Particulates and Biofiber Reinforced Lightweight Hybrid Sandwich Composites

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Abstract

Attempts were made to synthesis bio-fiber and fly ash particulates reinforced polymer matrix composite (PMC) sheets as well as to fabricate lightweight hybrid sandwich composites (HSC) using PMC as face sheet and polyurethane foam as core constituent. Mechanical properties and interfacial bonding of composite were studied. Results revealed that the PMC sheets showed the flexural strength of 116.59±19.37 MPa and flexural modulus of 2.66 ±0.45GPa with 1.7±0.02 g.cm-3 density. The low-density (0.84±0.02 g.cm-3) HSC exhibited 35.85 ±0.32 MPa flexural strength with 6.34±0.12 GPa flexural modulus. It is evident from this studies that presence of silica and alumina content in fly ash particulates together with the cellulosic content in bio-fibre enhanced the interfacial adhesion of core and PMC face sheets resulting enhanced flexural modulus of HSC. The resultant HSC has potential to use in construction industries, transportation system and packaging materials as an alternative material to wood and wood composites.

1. Introduction

Composites have been predominantly manufactured using synthetic polymer and fibres (glass, carbon, aramid) for use in a variety of applications. Manufacturing of glass fibre and other synthetic fibres are energy intensive and causes hazards to human health. Universally, environment threat due to exploitation of non-renewable resources is one of the prime concerns, which prioritizes the need of exploitation of renewable resources and recycling of waste materials for the development of new composite materials as an alternative to the conventionally used composites sheets and sandwiches for construction, automotive, locomotive and other commercial applications

Sandwich composites consists of skins elements or face sheets and core element. The concept is that the face sheets provide rigidity to sandwich and resists applied and bending stress whereas core element carries shear stress [1]. Sandwich composites are lightweight and offer better resistive stiffness against traction, compression, bending and impact loads [2]. Enhanced stiffness to weight ratio can be achieved by selecting proper face sheets and core materials [3]. The effect of raw material's properties, fiber matrix volume fraction and fiber orientation on mechanical properties of composites have been studied by several researchers where Polymethacrylimide, polyvinylchloride, polyurethane, and polypropylene foam are the commonly used core materials for synthesising sandwich composites [4,5,6,7,8]. The response of sandwich composites to impact load has also been studied by many researchers [9,10,11]. In general, low density and thermal conductivity, damage bearing capacity, high compressibility and adjustability of strength makes polyurethane as one of the most suitable core element. Polyurethane foam is closed cell structured syntactic foam. The stiffness and strength of foam largely depend on the density of solidified foam and foam structure [12,13]. Closed cell foam structure influences unremitting contact between skin and core materials providing better interfacial strength compared to other open cell structured core elements like rubber, plastics and metals. Usually, foam is stiffer and stronger in the direction of cell elongation [12,13,14]. It is reported that even if the skin material is damaged in hybrid sandwich composite, the core element exposed to external environment contributes to sustain the composites [15,16]. The high damage tolerance and low density of sandwich composites qualify for use in aerospace and other structural applications [17,18]. Ling et al. (2010), tested compressive, flexural and tensile properties of polyurethane foam reinforced with carbon nano-tube and found enhanced mechanical properties [19]. Highly compressed neat polyurethane having density of 0.196 g.cm^{-3} showed 1.6 MPa tensile, 30 MPa compressive and 51 MPa flexural strength and 45.5 MPa flexural modulus [19]. Sadighi et al.(2007), reported that densified Polyurethane foam can produce 6.15 MPa compressive strength with 274 MPa compressive modulus [20]. It is also reported that E glass vinyl ester polyurethane sandwich composites showed bending strength of 1.63 to 2.48 MPa with 1.0- 3.0 g.cm^{-3} density [21].

The summary of the results obtained by several researches on different natural fiber composites (NFC) are shown in Table 1. Mishra et al. (2000), reported that jute fiber epoxy composites with 40-60% fiber volume resulted in higher tensile (130-148 MPa), flexural (155-196 MPa) and impact strength (94-108 $Kj.m^{-2}$) as compared to jute polyester and jute polypropylene composites [22]. However, jute fiber vinyl ester composite showed good flexural (105-200 MPa) and impact strength (20-24 $Kj.m^{-2}$) [23,24]. The tensile (80.19 MPa), flexural (121.8 MPa) and impact strength (31.87 $Kj.m^{-2}$) of jute fabric polyester composite showed almost equivalent mechanical properties to that of jute epoxy composite [25]. Oksman et al., (2002) achieved high tensile strength composites (150-230 MPa) using sisal epoxy sisal polyester, sisal-vinyl ester and sisal-PP [26]. It is apparent from the earlier work that the jute polypropylene composite's tensile and flexural strength was about 28 MPa and 35 MPa respectively [27,28]. The tensile strength of jute fabric polyester, sisal polyester and sisal fabric vinyl ester composites were found to be as high as 80MPa, 70 MPa and 31MPa respectively [29,30,31]. But, sisal polypropylene composites showed a wide range of mechanical strength and are reported in Table 1 [32].

Table 1 Mechanical characteristics of different biofiber composites

S. No.	Composite	Fibre volume [%]	Tensile strength [MPa]	Tensile Modulus [GPa]	Flexural strength [MPa]	Flexural Modulus [GPa]	Impact strength [$Kj.m^{-2}$]	References
1.	Jute Epoxy	40-60	130-148	2.3-3.1	155-196	1.4-2.0	94-108	[22]
2.	Jute vinyl ester	8-35			105-200	4-12	20-24	[23]
3.	Jute Polyester	40-70	26-90	1.8-4.5	40-60	2.2-3.05	0.032-0.040	[24,25]
4.	Jute Polypropylene	10-20	28-35	2.5-3.0	35	-	18	[27, 28]
5.	Jute Fabric Polyester	-	80.19	9.58	121.8	7.64	31.87	[29]
6.	Sisal Polyester	40-50	29.66- 70	1.15-2.1	59.57-84	3.5-11.94	30-79	[26, 30]
7.	Sisal Fabric Vinyl ester	-	31.8	-	72.7	-	28.81	[31]
8.	Sisal Polypropylene	5-30	17-30	-	34-50	-	0.040-0.052	[32]
9.	Coir Polyester	10-35	15-26	12-20	20-36	-	0.27-0.96	[33]
10.	Coir Epoxy	7-30	13-21	6-7	35-54	1-2	17.5	[34, 35]
11.	PALF Polyester	10-40	17-64	1.5-2.5	35-80	18-32	3.5-22	[32]
12.	PALF Polypropylene	10-40	30-36	9-21	65-70	1.8-2	-	[37]
13.	Bannana Polyester	40	57-100	0.8-1.9	52-54	2.8	30-100	[38]
14.	Bannana Epoxy	35-40	44-50	1.8-2	53-74	1.5-1.9	6.95	[39]
15.	Bannana Vinyl ester	10-40	58-118	3.8-6	-	-	-	[40]
16.	Hemp Epoxy	40-65	130-162	12-18	175	10	14.8	[36,41]
17.	Flax Polyester	10-25	19-22	0.7-1.2				[42]
18.	Flax Polypropylene	-	20-35	4.2-17.5	48-56	3.4-5.7	19	[43]

Nevertheless, the tensile (15-30 MPa) and flexural (20-54 MPa) strength of coir epoxy / polyester composites did not show very high strength [33,34,35]. As compared to pineapple leaf fiber (PALF) and banana fiber composite, hemp epoxy composites showed high tensile (130-162 MPa) and flexural (175 MPa) strength [36]. High flexural strength (65-70 MPa) was recorded in pineapple fiber polypropylene composite [37]. The tensile strength of banana polyester (57-100 MPa), banana epoxy (44-50 MPa) and banana vinyl ester composites (58-118 MPa) found to be better than that of flax polyester and flax polypropylene composite [38, 39, 40]. Uses of cellulosic fibers in polymeric composites have drawn

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large interest as compared to glass and other synthetic fiber composites due to several environmental benefits and was discussed by several researchers [41,42,43]. Work done so far addressed only on the use of metal sheet or glass fiber laminates as a skin element in sandwich composites. Yet, no work has been reported to synthesis biofiber and fly ash particulate composite as face sheet to fabricate sandwich composites to achieve better mechanical strength. This paper deals with the demonstrated innovative techniques for synthesising biofiber and fly ash particulates reinforced composite (PMC) panels as a face sheets as well as fabrication of light weight hybrid sandwich composites (HSC) with improved materials performance.

2. Materials and Methods

2.1 Biofiber, fabric and flyash particulates

Commercial grade jute fabric, 320 GSM (gram per square metre) and fine grade fly ash particulates (< 160 micro meter) were used as a filler and reinforcing conditioner with polyester resin (Polylite PO-9123) for synthesising polymer matrix composite (PMC) sheets. Standard protocol was followed to characterize the tensile strength of jute fiber and jute yarn (ASTM 5526) and jute fabric (ASTM 5035) using Universal Testing Machine (UTM), 5 KN capacity, LRX Plus, Lloyd, UK. Particle size analysis of fly ash particulates was carried out using Laser Diffraction Particle size analyser (Model HELOS, Sympatec GMBH, Germany). Conductivity and pH was measured using Orion analyser (Model 1260, Orion Research Inc., USA) in a 1:2 solid: water suspension. For chemical analysis, flyash particulates were digested using microwave digester (QLAB 6000, Canada) and chemical constituents were analysed from the extracts by Atomic Absorption Spectrophotometer (Z-5000, Hitachi, Japan) with flame and graphite system. High purity water distilled from the Prima1-3 and Elgastat Maxima system England was used for all chemical analysis.

2.2 Synthesis and fabrication of PMC sheet and HSC

PMC sheets, thickness of 1.32 – 1.38 mm, were synthesized using jute fabric, polyester resin and fly ash particulates by hand layup technique followed by compression moulding. Bi-directional jute fabric was used as reinforcing medium as roving in the face sheets. Casting of the composite sheet was done under room temperature at 38 ± 2°C under 10 kg/ cm^2 pressure. The proportions of raw materials were: jute fabric (5-15 %), particulates (50-60 %) and polyester resin (35-40%) were suitably altered using each about 2 % accelerator (cobalt naphthenate) and hardener (Methyl ethyl ketone peroxide) for the fabrication of skin element.

The hybrid sandwich composite was fabricated using polyurethane foam (BAYFIT 33TA000 and DESMODUR - Polyol and diisocynate) as core constituent with the PMC sheets as outer skin. Polyurethane foam is a thermoset polymer, containing gaseous voids surrounded by a denser matrix which is either closed cell or open cell foam [44]. Sandwich composites were fabricated under injection followed by compression moulding system (180 kg/ cm^2) at room temperature (39 ± 1.5°C). Tensile properties of skin element and hybrid sandwich composites were tested according to ASTM D 638 using UTM, LRX Plus, Lloyd, UK. Tensile modulus and strain were evaluated from the stress-strain data. Flexural tests were performed according to ASTM D 790. Microstructure of the fracture surface of the hybrid composites was studied using Scanning Electron Microscope (SEM), Model JOEL JSM-5600 Japan. The hybrid sandwich composite fractured surfaces were sputter coated with a thin layer of gold to minimize the charging problem using JEOL-fine coat ion sputter.

3. Results and Discussions

3.1. Properties of biofiber, fabric and flyash particulates

There was a wide variation in the diameter of jute fiber and the average diameter was recorded as 90.91± 49.79 micro meters. Tensile strength of jute fiber was 317.67 ±78.23MPa with 25.65± 9.25 GPa tensile modulus.The diameter of jute fibre and bi-directional jute oven fabric is shown in Fig 1 and Fig.2. The tensile strength and tensile modulus of jute fiber yarn of 341.03± 6.21 micro metre in diameter showed 252.0 ± 75.7 MPa and 9.56 ± 1.42 GPa respectively.

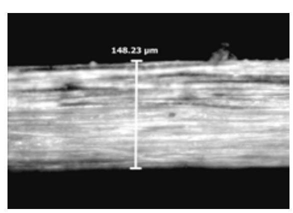


Fig. 1 Dia of jute fiber Fig.2 Jute oven fabric

Results revealed that jute fabric of 320 GSM grade showed a tensile strength of 18.07 ± 1.30 MPa with 0.20± 0.01 GPa tensile modulus (Table 2). In all cases, minimum triplicate samples were tested to validate the results.

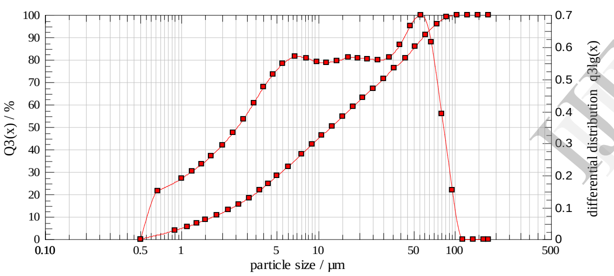
Table 2 Mechanical characteristics of jute fiber, yarn and fabric

Sample	Density [g/cm^3]	Tensile strength [MPa]	Tensile Modulus [GPa]	Elongation at Break [%]
Jute Fibre	1.43 ±0.02	319.67± 78.23	25.03±9.25	1.28 ±0.50
Jute yarn	1.33±0.04	252.0 ±75.70	9.56 ± 1.42	4.38 ±0.52
Jute fabric	251.67±10.41	18.07 ±1.30	0.2 ±0.01	19.27 ±2.81

Jute fabric density is expressed as gram per square meter (GSM)

Fly ash particulates consist of wide range of particles varying from clay to fine sand. Fig.3 shows the particle size distribution curve of fly ash particulates drawn from the particle size analysis data.

Fig. 3 Particle size distribution curve of fly ash particulates.



Results revealed that fly ash particulates consisted of about 16% clay sized particles, 75% silt sized particles and about 9% sand sized particles with specific surface area as high as 5.256 cm^2.gm^{-1}. Physico-chemical properties of fly ash are shown in Table 3. Fly ash particulate was greyish in colour exhibited specific gravity of 2.1. Porosity of fly ash particulates was 46.5- 49%. The pH was almost neutral (pH 7.2- 7.6) and electrical conductivity was 0.522 - 0614 dS/m. The major chemical constituents in fly ash particulates were silica, alumina and iron oxides. The other elements such as Cu, Zn, Pb, Cr, Cd, Co, Ni were present in low concentration (29 -120.7 ppm) and detailed results were reported and discussed elsewhere [45].

Table 3 Physico-chemical properties of fly ash particulates

Properties	Concentration
Physical Properties	
pH	7.20 - 7.60
Particle density	2.10 - 2.31
Specific surface area[m^2.gm^{-1}]	1.56 - 5.256
Porosity (%)	46.5 - 49.00
Electrical conductivity [ds.cm^{-1}]	0.522 - 0.614
Chemical Constituents	
Cu (ppm)	73..2 - 86.1
Zn (ppm)	36.6 - 42.8
Pb (ppm)	20.9 - 41.6
Cr (ppm)	69.4 - 88.4
Cd (ppm)	30.0 - 39.1
Co (ppm)	29.0 - 58.3
Ni (ppm)	99.2 - 120.7
Mn (ppm)	420 – 540
Mg (%)	0.481 – 0.644
Ca (%)	0.764 – 0.921
Na (%)	0.984 – 1.24
Fe (%)	3.64 – 4.82
Al (%)	15.38- 17.10
Si (%)	27.22 – 30.92

3.2 Mechanical properties of PMC and HSC

The average thickness of synthesised PMC sheet was about 1.35 mm (Fig.4). The tensile and flexural test specimen of PMC is shown in Fig. 5a and Fig. 5b respectively. From the findings, the average tensile strength and corresponding tensile modulus of PMC found to be 21.26 ±0.80 MPa and 0.802±0.062GPa respectively (Table 4). From the stress-strain diagram, it was recorded that the initial portion of the curve was linear at low strain rates followed by change in the slope of the curve indicating nonlinear behaviour of the material. The start of nonlinearity in the curve was an indication of the initial matrix crack followed by progressive failure of fibers and fly ash particulates. Aljibori (2011), reported that jute epoxy fabric composite resulted a tensile modulus of 1.5 GPa [46]. however, Rowell et al. (1996), reported a tensile strength and tensile modulus of jute fabric polyester composite in the range of 27 to 29 MPa and 2.6-3.1GPa respectively [47]. Saxena et al. (2008) explored the suitability of plant fibres with industrial wastes for synthesizing polyester based composites and reported that the incorporation of industrial waste particulates considerably improved the abrasive, wear and other mechanical properties of the composites [48]. In the present research jute fabric fly ash particulates composite (PMC) was used as the extreme layer for fabricating sandwich composites.

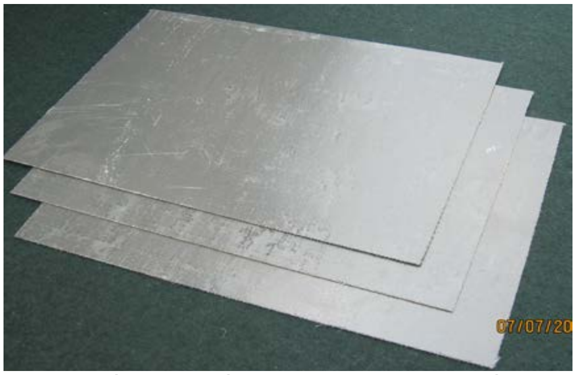


Fig. 4 Biofibre and fly ash particulate reinforced polymer matrix composite (PMC) sheets

Results showed that the average flexural strength of skin element was 116.59 ±19.37 MPa. The flexural modulus is a measure of the resistance required for deformation in bending which was found to be 2.66 ±0.45 GPa for skin element. Rowell et al. (1996) reported a flexural strength and flexural modulus of jute fabric polyester composite was in the range of 42 to 45 MPa and 2.2 to 2.5 GPa respectively [48]. It was observed that fly ash particulates reinforcement enhanced the flexural properties of jute fabric polymer composite as the presence of silica and aluminium oxides contributed in enhancing the composites' mechanical properties resulting to use as a potential face sheet in fabricating sandwich composites.

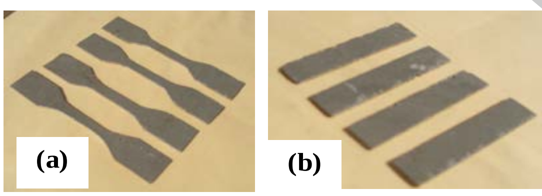


Fig. 5 (a) Tensile and (b) Flexural test specimens of PMC sheets

The dimension of fabricated hybrid sandwich composite was 32× 22×0.9 cm^3 (Fig. 6a). Carpentry work such as drilling, nailing, screwing and cutting required size is possible in the HSC (Fig.6b). The stress–strain diagram of hybrid sandwich composite is showed nonlinearity in the curve which is an indication of the initial matrix cracking followed by progressive failure of the fibers in skin and core materials. The average tensile strength of sandwich composite found to be 14.23 ± 0.63 MPa. The density of sandwich composites resulted in 66% lesser with respect to the face sheets which make it suitable for high value added engineering application. The strain at maximum tensile stress of composite varied from 6.68% to 7.05%. Tensile modulus was determined by the slope of the initial portion of stress-strain curves which was 0.36 ± 0.037 GPa.

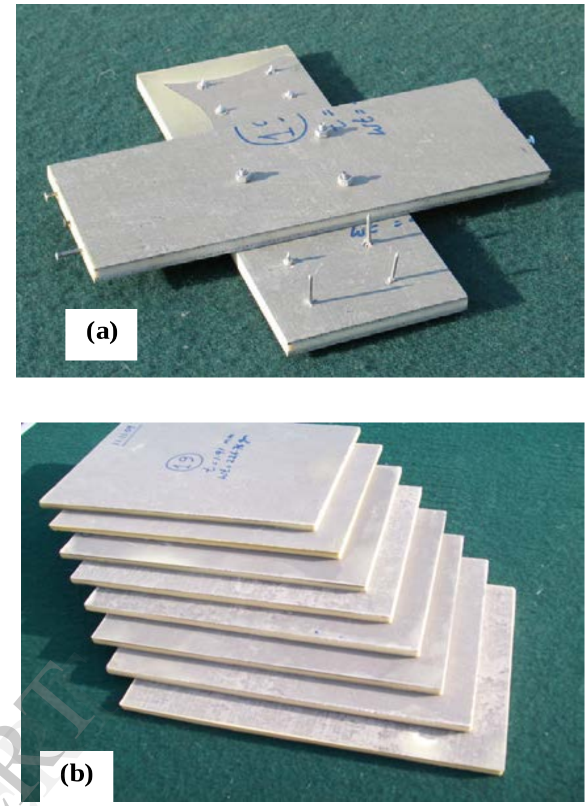


Fig. 6 (a, b) Hybrid sandwich composites

The flexural strength and flexural modulus of sandwich composite resulted 35.85 ± 0.32 MPa and 6.34 ± 0.12 GPa respectively (Table 4). The stiffness and strength of hybrid sandwich composite depends on the properties of face sheet and core materials and both have shown an initial linear response followed by a shorter nonlinear behavior before fracture. In fact, the flexural strength and stiffness was maintained by the strength of the extreme layers of reinforcement. Mirzapur et al. (2005) highlighted the de-bonding strength of skin element which plays an important role in enhancing the flexural rigidity and controlling the failure mechanism [3]. The glass-epoxy polyurethane sandwich panel with core having a density of 1.80-1.72 g/cc showed 3.8 - 11 MPa flexural strength and 283-386 MPa flexural modulus [3]. However, E-glass vinyl ester polyurethane sandwich composite showed better flexural stiffness as compared to core and skin stiffness [20]. In the present study, the mechanical properties were found enhanced with incorporation of biofibre and fly ash particulates as compared to the work done by other researchers [3,20].

Table 4 Mechanical properties of PMC face sheet and HSC

Properties	Face sheet (PMC)	Hybrid Sandwich Composite (HSC)
Density [g/cm^3]	1.7 ±0.02	0.84 ±0.02
Tensile strength [MPa]	21.26 ± 0.80	14.23 ± 0.63
Tensile Modulus [GPa]	0.802 ± 0.062	0.355 ±0.037
Elongation at Break [%]	2.674 ±0.68	6.89 ± 0.16
Flexural Strength [MPa	116.59 ±19.37	35.85 ± 0.32
Flexural Modulus [GPa	2.66 ± 0.45	6.34 ± 0,12
Impact strength (Kj.m^{-2})	293±2.26	4.76±0.23

3.3 Interfacial bonding of hybrid sandwich composites

The SEM microstructure of fracture surface of HSC is shown in Fig. 7. It is evident from the results that polyurethane foam is a syntactic foam type containing microballoons of size 30 µm – 200 µm (Fig.7 a,b and c). From the SEM micrograph, a very good interfacial bonding between polyurethane core and PMC sheet was recorded (Fig.7d). With regard to fracture failure, it is evident from the images that the fracture in foam occurred by crack propagation through struts and membranes perpendicular to the direction of loading. The SEM microstructure revealed that the fly ash particulates are spherical and some of them were hollow in shape. The microstructure, presence of silica and alumina in fly ash particulates and cellulose content in biofiber acted as reinforcement to increase the strength of composites and enhanced the interfacial adhesion between PMC and polyurethane foam. Pitts and fractured biofibers at fracture surface confirm the strong interfacial adhesion. Holes that formed in the SEM images indicate that some fibers and fly ash particles were pulled out during fracture failure (Fig.7 e and f). These fibers broke down or extruded because of the effect of larger tensile stress.

3.4. Potential application of hybrid sandwich composites

Full scale prototype of face sheet and sandwich composites size of 194×93cm^2 with varying thickness (12, 18 and 25 mm) with decorative colour finish and texture were also fabricated and optimised the process parameters. Fig. 8 (a, external view; b. internal view) shows the demonstrated structural cabin constructed using PMC sheets and HSC as flooring tiles, partition walls, roofing panels at the Building Materials Development Centre, CSIR- AMPRI Bhopal, India. The promising mechanical properties of low density hybrid sandwich composites have tremendous scope for use in structural and non structural applications such as walling, roofing, partition, flooring elements in construction, transport system and packaging industry. Besides better mechanical properties, the PMC sheets and HSC were found to be free from insects, fungus, termite and corrosion attack. The PMC and HSC developed in the present research programme have significant role for commercial use in composite industry. Further studies are in progress on the economic analysis of the PMC and HSC for commercial operation.

(a) External view

(b) Internal view

(c) Fig. 8. (a, b) Structural cabin constructed using PMC sheets and HSC at CSIR-AMPRI Bhopal, India

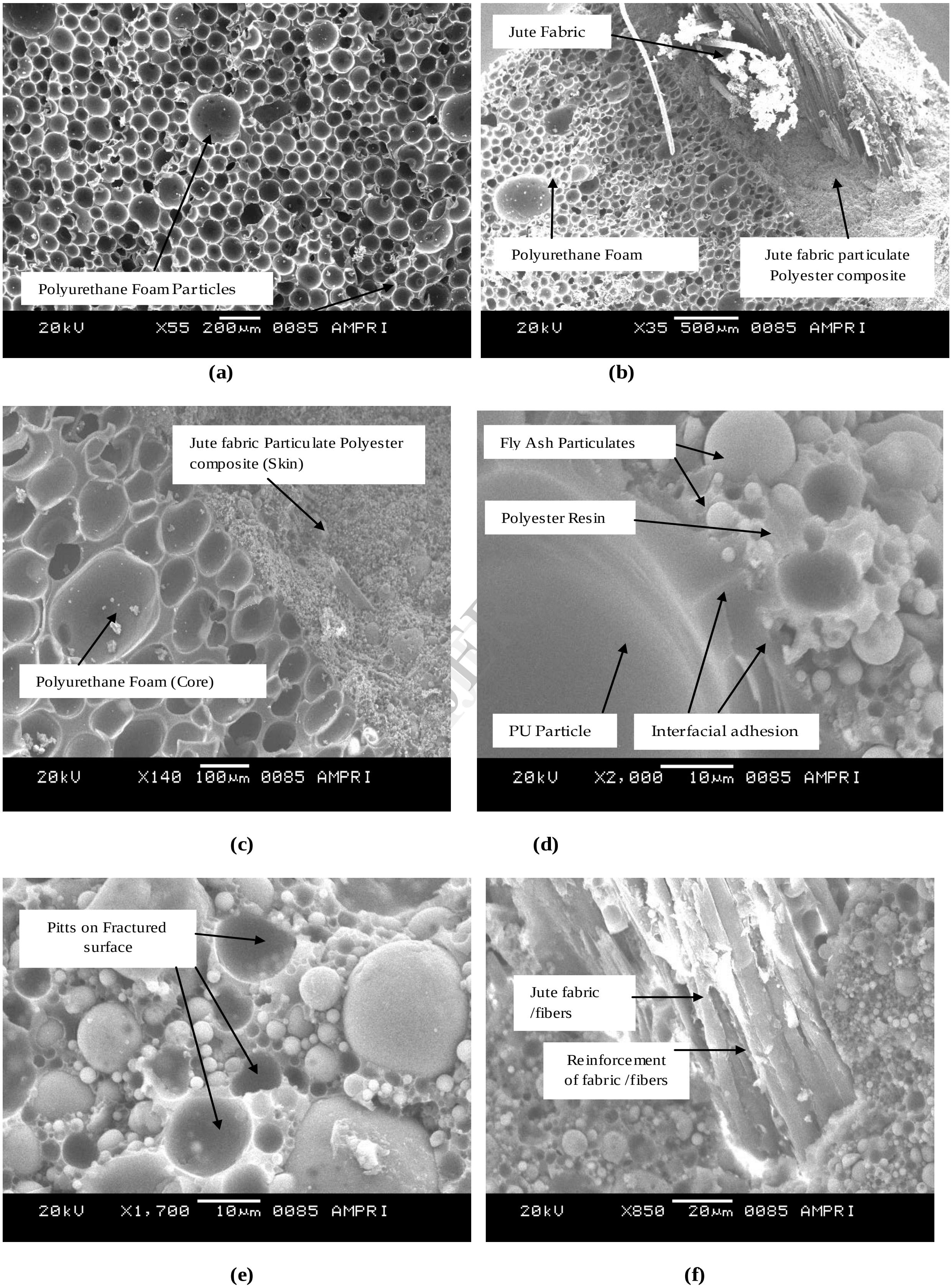


Fig.7 SEM Microstructure of fracture surface of hybrid sandwich composite

4. Conclusions

The present study demonstrated that biofiber and fly ash particulates can be used as a reinforcing medium to synthesis polymer matrix composite panels as well as a face sheet for fabricating polyurethane foam filled hybrid sandwich composites. Jute fabric / fibre and fly ash particulate reinforced polymer matrix composite sheets showed a tensile strength and tensile modulus of 21.26 ±0.80 MPa and 0.802±0.062GPa respectively. Results revealed that integration of biofibre and fly ash particulates enhanced the flexural strength (116.59 ±19.37 MPa) and flexural modulus (2.66 ±0.45 GPa) of sandwich composite's face sheet appreciably as compared to the work reported on jute-glass / polyester / epoxy composites. It is evident from the results that biofiber and fly ash particulates bounded hybrid sandwich composite exhibited a density of 0.8 ± g.cm^{-3} with 14.23 ± 0.63 MPa tensile strength and 35.85 ± 0.32 MPa flexural strength. Application of jute fabric and fly ash particulates enhanced its stiffness and strength. The outcome of the present study showed significant improvement in the mechanical properties of low density hybrid sandwich composites and also potentially explored the use of biofiber and fly ash particulates in replacing glass fiber and other synthetic fibers in making light weight sandwich composites. The promising mechanical properties of HSC have tremendous scope to use in wide range of applications as substitute to timber.

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