Biobased Composites For Structural Applications

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ABSTRACT

This study investigated the potential of plywood reinforced with short hemp fibers and bonded with lignin-phenol formaldehyde adhesives for structural applications. Furthermore, bond quality was examined by the evaluation of the physical and mechanical properties of the fabricated plywood as per standard methods of tests. The plywood bonded with phenol-formaldehyde resin was used as a control group. Four different types of plywoods were produced by the hot-pressing method. Subsequently, moisture content, density, modulus of elasticity, modulus of rupture, tensile strength, and matrix shear strength were tested and results were evaluated. Field emission scanning electron microscopy was used to analyze the fractured surface of tested plywood. The results indicated that lignin-phenol formaldehyde resin with a replacement of phenol up to 50 % weight with lignin (sodium lignosulfonate) can be utilized for bonding plywood. The modulus of elasticity of plywood bonded with lignin-phenol-formaldehyde resin at 7.65 GPa is higher than the phenol-formaldehyde resin at 5.28 GPa. The other properties of both lignin-phenol-formaldehyde and phenol-formaldehyde bonded plywood were found to be similar. In addition, the 3-point bending strength of plywood reinforced with short hemp fibers increased the strength of the composite by 95.3 MPa compared with the control group of 78.5 MPa. Furthermore, the moisture content, modulus of rupture, tensile strength, and shear strength test results of fiber-reinforced plywood confirm the specific requirements of structural plywood.

Keywords - bond quality; hemp; lignin; phenol; plywood, poplar

I. INTRODUCTION

The pressure to reduce carbon emissions and promote long-term sustainability is increasing in the built environment. In the construction industry, there is a need for materials that have a longer life cycle to reduce the impact of climate change. The vision of the European Forest-based products is to triple the biobased construction from the 2015 level and increased reuse and recycling by 70% by the year 2040 [1]. Engineered wood composites are a range of materials that can promote healthier buildings, low-carbon, and renewable products. Because these are produced by binding veneers, particles, fibers, and strands from wood with adhesives. They have a combination of properties that make them durable and stronger to use in diverse applications. Among these engineered wood products; plywood is one of the most commercially produced wooden panel products, and its global production has increased from 49 million m³ in 1993 to 107 million m³ in 2019 [2]. Commonly, plywood is manufactured by bonding wood veneers together with adhesives at elevated temperatures and pressure. It is practically defect-free, available in large dimensions, different sizes, and grades suitable for all uses due to its better dimensional stability, water-resistance properties, and high mechanical strength gained from layered construction [3,4,5]. Certainly, it is very beneficial from a circular economy point of view to develop bio-degradable plywood composites with least to no harmful effect on human health or the environment. There have been continuous efforts to make plywood more ecologically sustainable, with better strength, durability, and resistance to fungus attacks [6]. However, the characteristics of raw materials, such as wood species, reinforcements, and adhesive types play an important role in attaining the desirable properties of biobased wood panels. For the adhesives part in biobased composites; the phenol-formaldehyde resin matrix widely used in the plywood industry is produced from petroleum-based raw materials. However, the need to substitute fossil-based petrochemicals has led to extensive research on bio-based adhesives for sustainable production of biobased composites for the future [7]. Remarkably, the second most abundant natural aromatic polymer, lignin has phenyl propane units to replace phenol in adhesive formulations. Lignin is also a byproduct of the wood pulp and paper industries [8]. Lignin is a suitable substitute for phenol in the synthesis of phenol-formaldehyde resins due to its environmental considerations, comparatively low price, and phenolic moieties [7,9]. So, the research and development of different types of lignin-based adhesives for plywood production are gaining momentum [10]. Besides, lignin is currently being used as an additive in the matrix to enhance properties and reduce costs in plywood production [11]. However, the low reactivity of lignin with formaldehyde due to its sterical hindrance is a challenge that needs to be overcome [12]. At present, phenol could be partially replaced up to 50% in weight with unmodified lignin in commercial production. Recent studies have shown that the lignin application reduced the dust in manufacturing sites and improved the site's environmental condition as well [13,14]. Moreover, the methylolated Alcell lignin was used in phenolic resins and the successful fabrication of three-ply plywood was reported [15,24]. The 3 hrs. boiling water test showed good bonding strength and it was concluded that lignin-phenol-formaldehyde adhesives can be utilized in plywood manufacturing [16].

In addition, the shortage of renewable resources is a global concern and thus the wood sourcing from sustainably managed plantations is vital for the bioeconomy perception. Plantation timber such as poplar [*Populus* spp.] wood is widely used to produce plywood with medium-density with low strength properties [14,18,20]. The typical porous structure of poplar wood is conductive to the impregnation of adhesives. However, its weak strength and poor mechanical properties limit its usage in various products and applications. Therefore, it is important to improve the strength of poplar plywood and widen the scope of its application in construction, transport, and marine projects. Hence, the reinforcing technology with fibers in composites could be an effective method to improve the mechanical properties of wood composites made from plantation timber, too [20, 31]. The fiber reinforcement to poplar plywood may enhance the desirable properties required for its application. It is known that fiber-reinforced polymers are used to strengthen wood-based composites with the matrix such as phenol-formaldehyde resin. Besides, a significant increase in modulus of elasticity [MOE] of reinforced poplar plywood with glass fiber fabric was achieved [14]. In addition, the reinforcement reduced the variation between specimens of different directions when compared with control samples. The flax fiber-reinforced beech plywood influenced by different adhesive systems such as epoxy, isocyanate methylene diphenyl diisocyanate, and urea-formaldehyde was studied and the possibility of enhancing mechanical properties of plywood by using flax fiber reinforcement with various adhesives was found [13]. The research on high-performance plywood using carbon fiber reinforcement and poplar/eucalyptus veneers bonded with PF resin showed the improved modulus of elasticity and modulus of rupture of plywood based on the surface fiber reinforcement [31].

Furthermore, the addition of natural fibers into the composite matrix as fillers or reinforcements is increasing due to the eco-friendly values. The use of modified or unmodified hemp fibers can be effective for example with epoxy resin in reinforcement [21]. The hemp fiber composites are very tough and exhibit high strength, tolerate solvent, and are creep-resistant [21,22,24]. Similarly, an experiment on chemically treated hemp/glass fiber-reinforced composites and evaluation of their mechanical properties revealed the enhanced flexural strengths and were recommended as alternative materials to synthetic fiber composites [20,21,22,24]. Additionally, the preparation and evaluation of mechanical properties of fine fibers, sisal fibers and roselle fibers reinforced hybrid polymer composites in a phenol-formaldehyde matrix showed an increasein flexural strength and flexural modulus [23]. The strength and modulus of elasticity of hemp fibers found in the plant's outer layers are suitable for composite reinforcement. The versatile mechanical properties exhibited by these fibers make them suitable to replace existing glass fibers [24]. To date, very few studies were conducted utilizing natural hemp fibers and lignin-based adhesives in the manufacturing of plywood-type composites.

Hence, the study on producing biobased composites reinforced with natural fibers and bioadhesives is a much-needed approach to exploring the strength of the composite structure. Similarly, the different manufacturing techniques can be studied using low-density plantation timber plywood and its assembling parameters. Therefore, the purpose of this study is to synthesize lignin-phenol-formaldehyde resin and to produce plywood reinforced with hemp fibers using the hot-pressing method. Besides, physical and mechanical properties will be evaluated using destructive test methods to investigate the potential of reinforcement for the applications including the sheathing, cabinet, ceiling, and wall partition applications.

II. MATERIALS AND METHODS

A. Materials

Different types of plywood composites and adhesives were produced. Primarily, the veneers used for plywood were peeled from poplar wood [*Populus* spp.]. Natural hemp fiber [*Cannabis sativa* L.] was used as a reinforcement. The phenol-formaldehyde resin was used in the control group. All the materials chosen had been extensively studied for their implementation in commercial-scale production.

Wood veneers

The rotary cut veneers of poplar were used for the fabrication of plywood composite. Veneer sheets with an approximate thickness of 1.5-2.0 mm, length of about 1.2 m, and width of 0.6 m were generously supplied by M/s. BS Industries Pvt. Ltd., Mohali, India. The veneers were cut into the required sizes by using a Bosch table saw. These veneers were thoroughly dried to the moisture content of approximately 4-5 % before composite processing.

Hemp fibers

The hemp fibers [M/s. Go Green Products, Chennai, India] were acquired in a long fiber form of 1.8 m. The hemp fibers were treated with sodium hydroxide of 4 % by weight mixed with water. The hemp fibers were kept immersed for half an hour in NaOH solution. After that, the fibers were washed until the pH reached 7. Then, the hemp fibers were dried in a hot air oven at 60 °C for 12 hours. Later, the long fibers were cut to approximately 10-20 mm in length.

Adhesives

The phenol-formaldehyde resin was prepared in the molar ratio of 1:1.8 using NaOH as a catalyst. The condensation polymerization of 99% pure solid phenol [Fisher Scientific, Mumbai, India] and 37% solution of formaldehyde [M/s. Rankem, Thane, India] forms adhesive by the exothermic reaction. The mixture was kept at 90 – 92 °C for 90 minutes by providing external heat. The formation of milky white precipitation in the water indicatesthe polymerization of the phenol-formaldehyde resin. The viscosity of the resin prepared in hot conditions was 16 seconds when measured in a B4 cup as per IS 3944 test standard and pH @ 10. Likewise, the lignin-phenol-formaldehyde resin was prepared by replacing phenol with 50% of weight with sodium lignosulfonate. At first, the lignin was mixed with NaOH solution for 30 minutes for a better reaction with formaldehyde, and a similar process of PF resin synthesis was employed. Finally, the resin was transferred and stored for plywood manufacturing.

B. Methods

Fabrication of plywood

Primarily, two raw materials are required to produce plywood; one is wood veneers and the other is adhesives.The hot-pressing method was mentioned in most of the research literature on plywood composite to bind veneers to make desirable composite as shown in Figure 1. A total of 5 ply veneer construction was chosen to make plywood with the grain direction perpendicular to each other and the plan described in Table 1. Out of five veneers, two veneers were applied with PF resin using a brush, and the amount of adhesive spread was kept at 0.35 $kg.m^{-2}$. Whereas each resin matrix was loaded with 215 $g.m^{-2}$ of short hemp fibers. The fibers were randomly oriented on the plane of the wood veneers. The 100 kN hot press [N.K. Industries, Yamuna Nagar, India] equipped with electrical heating was used for making plywood. The temperature was kept around 135±5 °C and pressure at 12 $kg.cm^{-2}$ for 12 minutes as a regular manufacturing process followed in most of the mills.

Table 1 Experimental sample plan of plywood fabrication

Plywood type	Plies	Code
Poplar + Phenolic Adhesive	5 plies	PF
Poplar + Short Hemp + Phenolic Adhesive	5 plies + hemp	PFF
Poplar + Lignin Phenolic Adhesive	5 plies	LPF
Poplar + Short Hemp + Lignin Phenolic Adhesive	5 plies + hemp	LPFF

Fig. 1 Short hemp fibers and veneer assembly [a], resin application by using brush [b], plywood assembly for hot pressing [c], test specimens [d]

Properties of Plywood

The biobased composites shall have certain properties to be used in structural applications and it is clearly stated in many international standards. Among the many test parameters, the moisture content, density, modulus of elasticity, modulus of rupture, tensile strength, and matrix shear strength tests were performed and evaluated for the present study. A total of eight plywood samples were prepared and plywood bonded with PF resin was used as a control group. The test specimens of different sizes were prepared as per the relevant standard test methods with five test specimens for each test. All the test specimens were prepared using a Bosch Table saw and a Bosch jig saw machine. The 3-point bending strength for modulus of rupture [MOR] and modulus of elasticity [MOE] were tested based on the IS 1734 standard. The analysis of tensile strength was done according to IS 1734 standard. All tests were done with K-TEST SERIES universal testing machine UTM [Kalpak Instruments, Pune, India].

The modulus of elasticity of the plywood is one of the most essential parameters to know for the load-bearing capacity. Samples were tested according to IS 1734 standard [part 11 static bending strength]. The specimens were cut along the grain direction and the length was 20 times the thickness of the plywood + 50 mm and the width of 50 mm. A total of six specimens were cut from each type of plywood. The MOE was calculated using Formula 1 and MOR was calculated according to formula 2. P is load in N at the proportional limit, P' maximum load. L span length, b width, t thickness, and Δ are deflection at the proportional limit.

$$\text{Modulus of Elasticity [MOE]} = P L^3 / [4\, b\, t^3\, \Delta] \qquad [1]$$

The modulus of rupture of the plywood was measured as per IS 1734 [part 11]. The specimens used to test the MOR were similar to specimens in the MOE testing. The samples for this test were prepared to align the long edge of the test specimen to the grain direction of the surface veneer. Matrix shear strength was determined through the tensile shear test perpendicular to the surface of the board, according to IS 1734 standard.

$$\text{Modulus of Rupture [MOR]} = 3\, P'L / [2\, bt^2] \qquad [2]$$

The tensile strength is measured as the load applied on a cross-sectional area of plywood in tension. The specimen size was 50 mm in width and length of 305 mm and the curvature was cut using a template as per IS 1734 [part 9]. A total of five test specimens were cut using a Bosch Table saw and Bosch jigsaw. The test specimen was fixed in between jigs of UTM and pulled in tension mode. The breaking load [L] value was recorded, and tensile strength was calculated using formula 3.

$$\text{Tensile strength} = L/[bt] \qquad [3]$$

The bond strength of the adhesive can be evaluated by the matrix shear strength test. It was tested as per IS 1734 [part4]. A total of 10 test specimens were taken from each type of plywood. The breaking load was recorded as the matrix shear strength of the test specimen. The wood failure in the matrix was recorded as well.

Statistical analysis

The results of the determination of the physical and mechanical properties of plywood were statistically analyzed using MS EXCEL and R Studio. For significant differences between factors, analysis of variance [ANOVA] at a 0.05 significance level was used. A comparison of the means was performed by the Tukey-Kramer test, with a 0.05 significance level.

SEM

Field emission Scanning electron micrographs of the fractured surface of the composite specimens were acquired using an FE-SEM JEOL-JSM [JEOL, Tokyo, Japan] to study morphology [21,22]

III. RESULTS AND DISCUSSION

The mean and standard deviation values of moisture content, density, and mechanical properties such as modulus of rupture, modulus of elasticity, tensile strength, and matrix shear strength of all four types of plywoods are presented in Table 2 and illustrated in the form of box plots as shown in Figure 3. The comparison among the four different plywoods can highlight the changes brought by the reinforcement of short hemp fibers bonded with lignin-phenol-formaldehyde resin. After pressing, the plywood was found to be intact without any visual defects. The drying of wood veneers and short hemp fibers to attain moisture content of approximately 4-5 % helped to produce high-quality plywood. Moreover, no face chipping or surface delamination was observed during the cross-cutting and test specimen preparation process. Furthermore, the phenol-formaldehyde resin [PF] and lignin-phenol-formaldehyde resins [LPF] were synthesized and attained the required pH, water tolerance, and viscosity. The moisture content [IS 1734: 2018 Reaffirmed, Part 1] results are presented in Table 2 [28]. The low moisture content of LPF plywood 6.0 % as per Table 2 might be due to the softening of unreacted lignin in the LPF polymer network during the fabrication process and is consistent with the literature [11]. The sediment formation of unreacted lignin at the bottom of the resin kettle was observed afterthe LPF resin synthesis. In addition, the evaporation of moisture during the hot pressing at a temperature of 140°C may lead to a low moisture content of LPF plywood with a firm cross-linking of the lignin binder with wood.Moreover, the research on the thermo-plastic behavior of lignin-phenol formaldehyde [11] has indicated that the LPF samples exhibited a low moisture content during the accelerated bond strength development.

Furthermore, the addition of short hemp fiber to plywood [PFF] has shown less moisture content 7.3% in comparison with the control sample of 8.1%. Further, the densities of the PF 0.59 g.cm^{-3}, PFF 0.60 g.cm^{-3}, LPF 0.62 g.cm^{-3} and LPFF 0.61 g.cm^{-3} are recorded in Table 2 and found to be similar and within statistical variation. This is due to the use of the same species of wood veneers for plywood fabrication. Further, the addition of short hemp fibers 215 g.m^{-2} did not affect the density of the plywood.

Table 2 Physical and mechanical properties of all four types of plywood

Tests		PF	PFF	LPF	LPFF
Moisture Content (%)	Mean	8.1	7.3	6.0	6.5
	Sd	(0.2)	(0.2)	(0.3)	(0.1)
Density (g.cm^{-3})	Mean	0.59	0.60	0.62	0.61
	Sd	(0.01)	(0.01)	(0.01)	(0.01)
Modulus of rupture (MPa)	Mean	78.5	95.3	82.0	66.9
	Sd	(10.2)	(9.0)	(9.3)	(13.4)
Modulus of elasticity (GPa)	Mean	5.28	5.71	7.65	5.56
	Sd	(0.6)	(0.6)	(0.8)	(0.3)
Tensile Strength (MPa)	Mean	47.71	60.74	67.67	53.44
	Sd	(5.5)	(17.0)	(16.4)	(13.6)
Matrix Shear Strength (N)	Mean	1289	1285	833	863
	Sd	(270)	(282)	(135)	(115)

Moreover, the modulus of elasticity results showed a higher value for LPF plywood 7.65 GPa in comparison with PF plywood 5.28 GPa based on a *t-test* comparison of means *p-value* < 0.05. The one-way ANOVA test on the four groups showed that there is a difference in means between the groups with a *p-value* < 0.0. In addition, the Tukey-Kramer post-hoc test for PF-LPF group comparison showed a *q-statistic of* 9.987 < 3.96. Moreover, the higher modulus of elasticity of LPF plywood could be due to the high viscosity of the resin. Small parts of unreacted lignin may be fixed onto wood cells at high pressure and temperature compared with PF adhesive.

Besides, the addition of short hemp fiber [PFF] showed an increase in modulus of elasticity of 5.71 GPa of plywood. The short hemp fibers are embedded into the matrix as shown in figure 3 and enhanced the load-bearing capacity during the bending test as expected and reported by other research literature. A similar trend can be found in the case of modulus of elasticity of LPFF plywood 5.56 GPa in comparison with PF plywood. However, there is a standard deviation of more than 10% within the group is observed for modulus of elasticity. It may be due to the hand layup method to spread the short hemp fiber as shown in figure 1a that it was uneven and randomly placed could cause voids on the surface area of plywood. Overall, the addition of short hemp fiber of 215 $g.m^{-2}$ showed an effect on the modulus of elasticity of the plywood. An increase in modulus of rupture [MOR], modulus of elasticity [MOE], and tensile strength [TS] was observed for plywood reinforced with short hemp fibers [PFF] compared with the control group [PF] which is consistent with the literature [13,25,30].

In addition, based on the *t-test* on comparison of means of PF and PPF plywood [*p-value* < 0.05], the addition of short hemp fibers has increased the modulus of rupture of the plywood significantly in PPF plywood 95.34 MPa in comparison with the control group PF plywood 78.5 MPa. The reason may be the strong reinforcement effect of hemp fibers with the matrix. The bonding between veneers, fibers, and resin matrix is intact due to the hot pressing. The polymer resin impregnated into the surface of fibers and into voids that could have enhanced the compatibility and adhesion between the fiber and the matrix [2]. The short hemp fibers could give extra strength to the plywood due to their modulus of elasticity and high aspect ratio; which make them desirable for composite production. Moreover, alkali-treated hemp fibers are shown to have better flexural strength than untreated hemp fibers [21, 24]. Besides, the MOR of LPF plywood 82 MPa is slightly higher than that of the PF control group 78.5 MPa and within the statistical limit. It may be due to better impregnation of LPF adhesive into wood veneer surface to form a perfect composite matrix. In addition, the unreacted lignin particles could have stuck to the interface of the voids in the wood veneer assembly. This implies that the lignin-phenol-formaldehyde resin is suitable for plywood bonding [3,9,16]. Moreover, the results of the tensile strength showed that the hemp fiber reinforcement has increased the tensile strength of the plywood PFF 60.74 MPa in comparison with PF plywood 47.71 MPa which is consistent with the literature [22]. The short hemp fiber of 10-20 mm length merged with phenolic adhesive and wood to form a better composite matrix. During the assembly of plywood composite, micro-voids are formed along with the individual fiber tows and matrix resulting in standard deviations in mechanical test results.

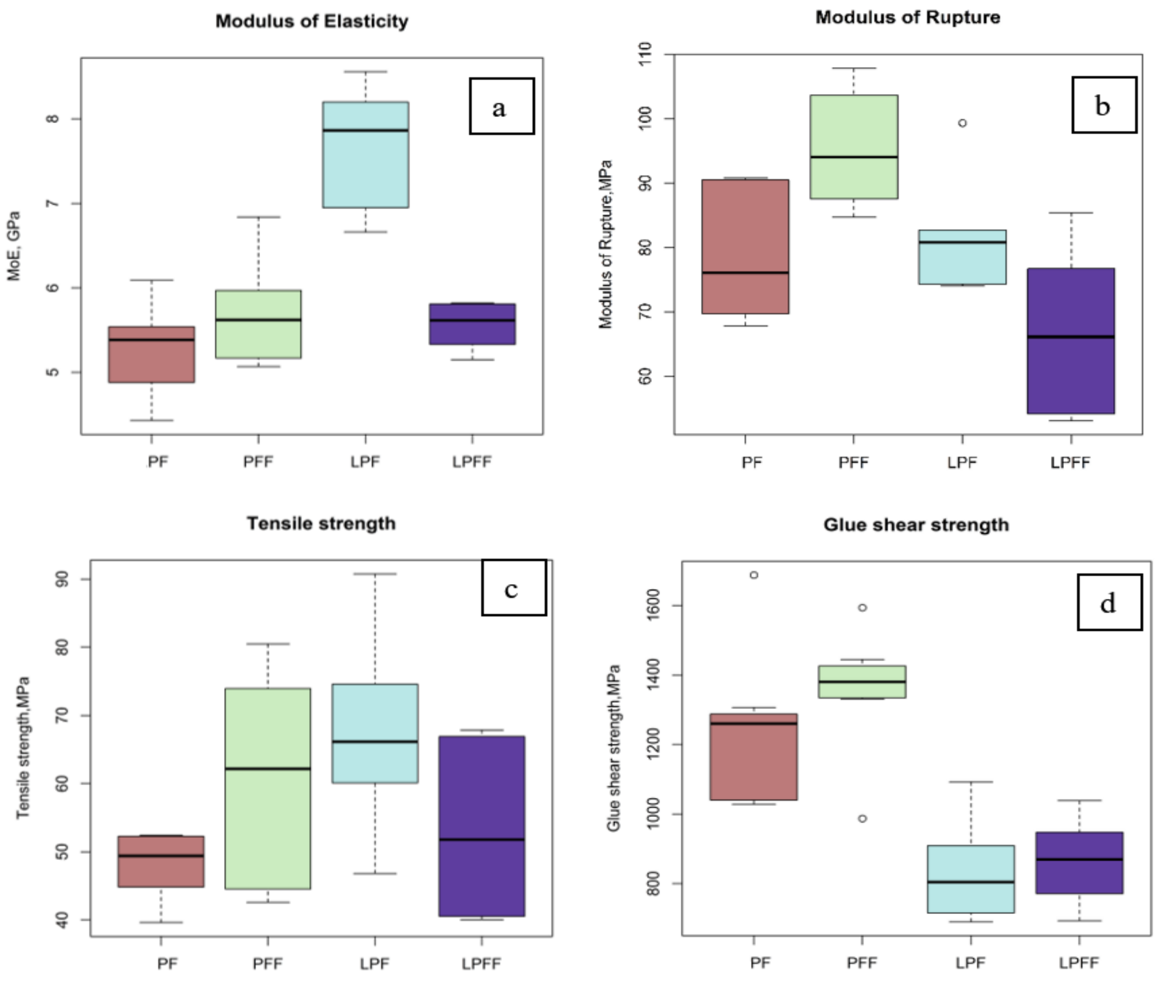

Fig. 2 Box plots of the MOE [a], MOR [b], tensile strength [c], matrix shear strength [d]

Moreover, the plywood bonded with lignin-phenolic adhesives [LPF] showed a high tensile strength of 67.67 MPa compared to that of control plywood. It indicates that the lignin phenolic adhesives have the tensile strength of plywood similar to that of phenolic adhesives by forming a polymer composite. Whereas the TS of plywood reinforced with short hemp fibers and lignin adhesives LPFF is 53.44 MPa that showed similar tensile strength as the normal plywood [PF]. In addition, the tensile strength results show that it largely depends upon the strength of wood veneers and the reinforcement has a minimal effect. Furthermore, the matrix shear strength test results show that the lignin phenolic resins are low in strength when compared with the control group phenolic adhesive [PF]. This may be due to the unreactive nature of lignin with formaldehyde as the phenolic groups are not completely cross-linked with formaldehyde. Furthermore, reinforcement of short hemp fiber has shown no effect on the shear strength of the plywood. Although hemp fiber reinforcement shows an increase in modulus of rupture and modulus of elasticity of plywood, its shear strength is weak in the tensile direction. In addition, the matrix shear strength of the LPF resin group is significantly less compared with the PF plywood group which is consistent with the literature [26, 32,33].

Nevertheless, a slightly high standard deviation was observed in test results due to the voids in the composite fabrication. The random spread of short hemp fiber as shown in figure 1 could have resulted in variation and standard deviation in results. Besides, wood veneers may have contributed to the standard deviation among the test results as the wood itself is a heterogeneous mixture. In addition, the test results of the fabricated composite were compared with the specific requirements of the structural plywood as per IS 10701. The moisture content of all three PFF, LPF, and LPFF plywood are within the limits of 5-15%. For matrix shear strength, PFF plywood results of 1285 N are close to the specific requirements of 1100-1350 N. Besides, the modulus of rupture and tensile strength of PFF, LPF, and LPFF plywoods is passing the required limits. However, the modulus of elasticity test results is below the specific requirements when tested along the grain direction [29].

MORPHOLOGICAL STUDIES

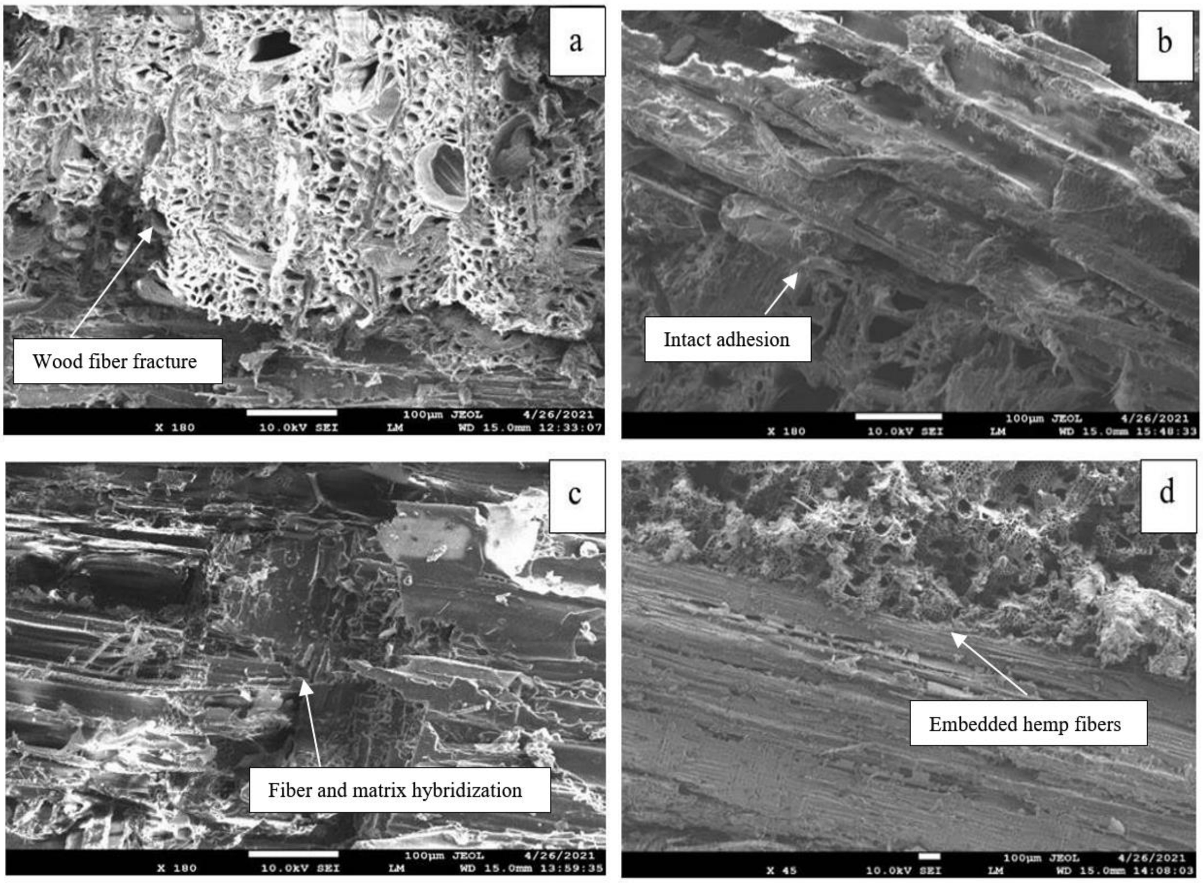

Fig. 3 FE-SEM micrographs of the fractured surface of PF plywood [a], PFF plywood [b], LPF plywood [c], and LPFF plywood [d] after tensile strength test

From Figure 4b, it is clear that the adhesion of the short hemp fiber with polymer matrix in the interfacial area is very intact. No spaces between the hemp fiber and the PF matrix and no fiber pullout can be seen, indicating strong fiber impregnation in the polymer matrix with strong adhesion.

This impregnation allowed the fiber to transfer load while pulled out, which was responsible for the high strength of the PFF composite. Figures 4c and 4d show an FE-SEM micrograph of the LPF and LPFF hybrid composite after the tensile test. It can be seen from Figure 3d that the hemp fibers are tightly embedded in the LPF resin without voids at the interfacial province between the hemp fibers and the LPFF matrix. The hemp fiber reinforcement of LPF plywood showed a similar modulus of elasticity and flexural properties as compared with the control groupPF [Figure 2]. The mechanical interlocking between the fibers and the matrix appeared to be good, which could beattributed to the chemical bonding that resulted from optimum hybridization and occurred between the fibers and the matrix [Figure 4c, 4d]. It is possible that reactions occurred between the chemical compounds of the phenolic adhesives and hemp fibers. Overall, the FE-SEM study suggests that the natural fibers bonded well into plywood composites and did not show fiber pullout from the polymer matrix. Therefore, this type of hybrid composite maybe used to enhance the mechanical properties of plywood made by using low-density wood.

However, a few limitations of the study including the spreading of short hemp fiber onto the veneer surface area was not so uniform due to the size of the fibers and hand layup method. Besides, the sodium lignosulfonate used in the LPF resin synthesis was not evaluated for its characteristics in the present study. So, furtherstudies could be conducted by producing more plywood boards in larger groups. In addition, the present study has shown the high modulus of elasticity of LPF plywood in comparison with other groups. This could be verified by repeating the plywood fabrication and its evaluation. Moreover, the increase in the volume of hemp fibers, their orientation, and more uniform spreading on plywood could be studied to develop better composites. Besides, the lignin-based adhesive should be optimized for commercial production. LPF adhesives synthesized with high reactive lignin could be studied along with higher replacement of phenol in the adhesives.

IV. CONCLUSIONS

This study fabricated the plywood reinforced with natural hemp fiber and lignin-phenolic adhesives without major defects. Mechanical and physical tests were conducted as per standard methods of tests on plywoods regarding the strength and bonding of bio-based resins and reinforcement of hemp fibers. To conclude, the results of the study indicate that hemp fiber reinforcement enhanced the modulus of rupture of plywood at 95.3 MPa compared with PF plywood at 78.5 MPa. The phenol can be replaced by lignin (sodium lignosulfonate) up to 50% in weight in lignin-phenol-formaldehyde resin. The modulus of rupture test results of LPF 82 MPa show the strong adhesion of wood veneers by lignin phenolic adhesives. The modulus of elasticity of LPF plywood 7.65 GPa is higher than the PF control group 5.29 GPa. In addition, the LPF plywood matrix shear strength test of 833 N results was lower compared with PF plywood 1289 N. Furthermore, the results of moisture content, MOR, TS, and shear strength confirm the structural plywood specification as per IS 10701. Hence, the bio-based composites reinforced with short hemp fiber and bioadhesives can be used in structural applications including sheathing, cabinet, ceiling, and wall cladding applications.

V. ACKNOWLEDGMENTS

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