Evaluation of Physical and Mechanical Properties of Fiber-Reinforced Poplar Scrimber

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The mechanical properties of poplar scrimber reinforced with glass fiber mesh were investigated. The influence of the different structures and densities were studied with respect to the modulus of rupture (MOR), modulus of elasticity (MOE), and impact toughness (IT). The glass fiber improved the mechanical properties of poplar scrimber. The MOR, MOE, and IT of the scrimber had an obvious dependence on the number of glass fiber layers. When the layers of glass fiber meshes were increased, the MOR, MOE, and IT were increased compared to the control group (scrimber without glass fiber reinforcement). The MOR, MOE, and IT of single-layer glass fiber reinforced scrimber increased a lot compared to the control group. The MOR, MOE, and IT of double-layer glass fiber reinforced scrimber (DGRS) were increased, but the amplitude of the increase was smaller than that of SGRS. Compared to the MOR, MOE, and IT of DGRS, the MOR, MOE, and IT of triple-layer glass fiber reinforced scrimber (TGRS) decreased slightly. When the density was increased, the increasing rate of the MOR, MOE, and IT of the glass fiber reinforced scrimber showed a downward trend, and the glass fiber had better strengthen effects on the scrimber at low density (0.6 g/cm^3 and 0.7 g/cm^3).

Keywords: Wood scrimber; Glass fiber; Density; Mechanical properties

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INTRODUCTION

To solve the shortage of solid wood in China, poplar has been widely cultivated and used in the wood industry because of its short growing period (Burdurlu *et al.* 2007; Dong *et al.* 2016). However, because of its weak mechanical properties and loose material, the application of poplar in construction material is limited. Innovating and perfecting the reinforcement technology to improve the physical and mechanical properties of poplar products and to increase the use of poplar products is very important (Wang *et al.* 2015).

Scrimber is a restructuring wood product made from wood bundles treated by rolling, and it has a high material utilization rate (He *et al.* 2016). Scrimber preserves good quality solid wood in processing and eliminates most defects of solid wood (Yu and Yu 2015). However, the horizontal properties of scrimber are relatively low, and its comprehensive performance is not perfect. Because wood bundles are too thick, its thickness swelling rate after water absorption is relatively high (Yu and Yu 2013; Zhang *et al.* 2016).

Glass fiber is an inorganic, non-metallic material with excellent properties. Because of its good mechanical properties and economic benefits, glass fiber has been widely used as a reinforcement material in the wood industry (Carrubba *et al.* 2008; Granse *et al.* 2013; Cheng *et al.* 2015). Mariam *et al.* (2012) studied the addition of glass fiber and wood flour in recycled polypropylene (RPP). The tensile strength of the composites was significantly increased by adding glass fiber. Glass fiber also increased the hardness of the composites. Supreeda *et al.* (2012) studied the wear behaviors of glass fiber reinforced wood and PVC composites, showing that the flexural strength and the wear resistance of the composites were increased with the addition of glass fiber. Turku and Karki (2014) studied the effects of four different reinforcing fibers on the mechanical properties and dimensional stability of wood plastic composites. The study indicated that the tensile strength and modulus of the glass fiber reinforced composites had a clear improvement, but the impact toughness were reduced by 7%. Bal (2014) investigated the effects of different structures and adding different percentages of woven glass fiber on reinforced laminated veneer lumber (LVL). The research indicated that using woven glass fiber to reinforce the LVL had both positive and negative effects on mechanical properties of LVL. Wang *et al.* (2011) tried to enhance LVL by adding ramie glass fiber. The study showed that the ramie fiber had a positive influence on the mechanical properties; in addition, the shear strength had an especially great improvement. Another study showed that the mechanical properties of LVL can be greatly improved by adding reinforced glass fiber (Pirvu *et al*. 2004).

Although glass fiber has been widely applied in the reinforcement of wood composites such as LVL and plywood, research on glass fiber reinforced scrimber has not been widely reported. The aim of the present study was to evaluate the effects of the density and structure on glass-fiber reinforced scrimber.

EXPERIMENTAL

Materials

Fibrous veneer strip

The scrimber was made of fibrous veneer strips in this paper. Fibrous veneer strip means that the strip is produced by untwisting, such that the longitudinal fiber is not broken and the thickness of fiber remains uniform.

The poplar veneers were provided by Power Dekor Group Co., Ltd. (Jianou, China). They had an initial moisture content of 8%, average density of 0.402 g/cm^3, and thickness of 2 mm. The poplar veneers were first split into approximately the same sizes, and the veneers were rolled into small strips, 20 mm in width and 1870 mm in length, by an untwisting machine. Finally, the roller pressure was decreased by adjusting the distance of the idler wheels on the untwisting machine. The poplar veneers were cut into fibrous veneer strips that were cross-linked in the width direction with no fracture alone the length direction.

Reinforcing fiber

The glass fiber mesh was woven, using glass fiber in both the length and width directions. The glass fiber mesh was 5 mm by 5 mm, and its unit density was approximately 200 g/cm^3. As Table 1 shows, the mechanical properties of single glass fiber were much better than those of poplar fiber. The mass fraction of glass fiber reinforcement in each type of scrimber and each density is shown in Table 2.

Table 1. Mechanical Properties of Single Fiber

Fiber Category	Tensile Strength (MPa)	MOE (GPa)	Elongation (MPa)
Glass fiber	≧1400	≧71	≧2.1
Poplar fiber	≧700	≧30	≧1.7

Table 2. Mass Fraction of Glass Fiber Reinforcement

Structure \ Density	0.6g/cm^3	0.7g/cm^3	0.8g/cm^3	0.9g/cm^3
SGRS	2.2%	1.9%	1.7%	1.5%
DGRS	4.4%	3.8%	3.3%	3.0%
TGRS	6.7%	5.7%	5.0%	4.4%

Preparation of the Materials and Specimen

As Fig. 2 shows, the reinforced scrimber was fabricated as follows. The glass fiber was treated on the surface through soaking in the coupling agent KH550 for 20 min. The concentration of the coupling agent was 2%. The glass fiber meshes were air-dried for 3 days. Next, the glass fiber meshes were soaked in phenol formaldehyde (PF) resin (of 43.52% solids) for 20 min and then dried at 120 °C for 20 min. The fibrous poplar veneer strips were soaked in PF for 20 min and then dried in a chain drying furnace at 80 °C for 90 min. The moisture content of the fibrous poplar veneer strips after drying was approximately 12%. When preparing the layup, the treated glass fiber meshes were added in the mat. Finally, the composite was hot-pressed at 140 °C and 120 MPa until the PF was cured. After hot-pressing, the dimension of the mat was finally 2440 × 1220 ×33 mm. As shown in Fig. 2, the specimens were divided into 4 types of structure: the control group (without glass fiber reinforcement), single-layer glass fiber reinforced scrimber (SGRS), the double-layer glass fiber reinforced scrimber (DGRS) and, the triple-layer glass fiber reinforced scrimber (TGRS). The position of the glass fiber meshes was also shown in Fig. 2.

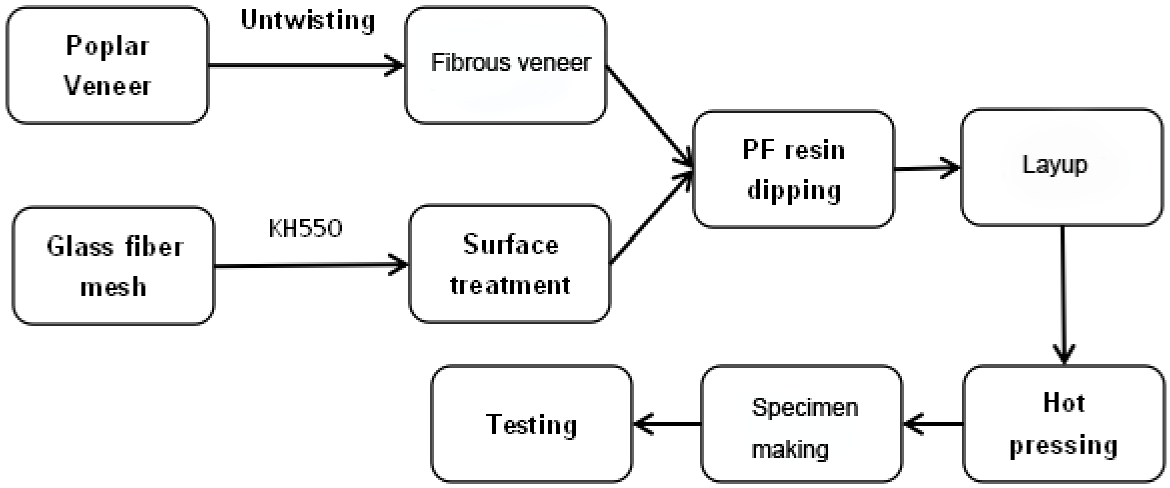


Fig. 1. Production processing of glass fiber reinforced scrimber

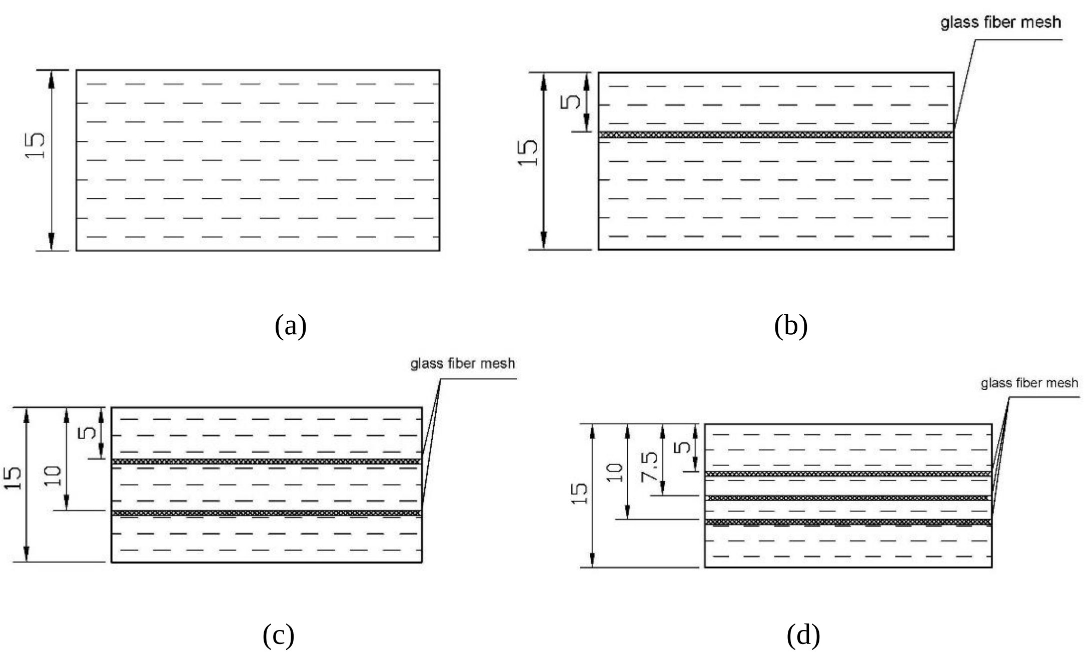
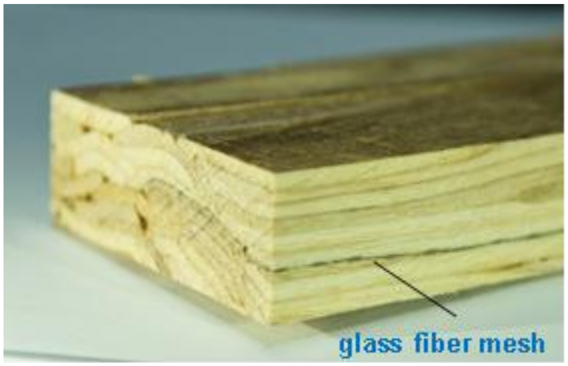


Fig. 2. Three types of poplar scrimber for construction: (a) control group (without glass fiber reinforcement), (b) single-layer glass fiber reinforced scrimber, (c) double-layer glass fiber reinforced scrimber, and (d) triple-layer glass fiber reinforced scrimber

The position of glass fiber in the final pressed board is shown in Fig. 3. The glass fiber was oriented lengthwise, while in the width direction there was a degree of bending.



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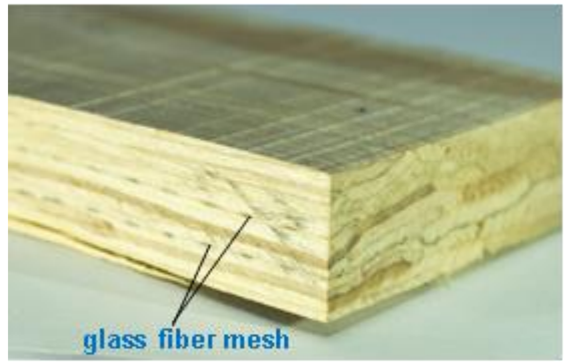


(b)

(c)

Fig. 3. **(a)** The specimen of SGRS, **(b)** The specimen of DGRS, **(c)** The specimen of TGRS

By controlling the weight of the raw materials added in the slabs, the specimens were also set into four different density levels: 0.6 g/cm^3, 0.7 g/cm^3, 0.8 g/cm^3, 0.9 g/cm^3, and each kind of specimen with different constructions were divided into 4 density levels.

Measurement of Mechanical Properties

The mechanical properties measured included modulus of rupture (MOR), modulus of elasticity (MOE), and impact toughness (IT). The reinforced scrimber was cut into testing specimens according to the Chinese National Standard GB/T 20241-2006 (2006). The MOR and MOE were measured through a three-point bending test by universal mechanical testing machine (TST-B615A-S, TST Detection Instrument Co. Ltd., Dongguan, China). During the testing of the SGRS, the side that was away from the reinforced material was contacted with the hammer. The specimen dimensions for MOR and MOE testing were 400 mm × 50 mm × 15 mm (Length × Width × Thickness).

The IT was also measured according to the Chinese National Standard GB/T 20241-2006 (2006). The dimensions of testing samples for IT testing were 300 mm × 50 mm × 15 mm (Length × Width × Thickness). The specimen was set on the support of testing machine (MTS-ZCJ2000, MTS System Instrument Co. Ltd., Guangzhou, China) symmetrically and then was broken by the free falling hammer. The energy absorbed by the specimen during breakage was recorded by the testing machine and the IT was finally calculated by the following formula,

$$A = \frac{1000Q}{b \times t} \quad (1)$$

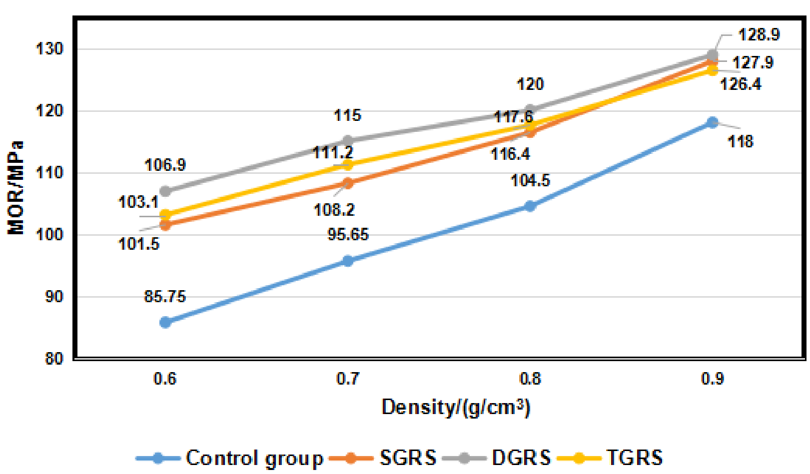
where A is the impact toughness of the material(KJ/m^2), Q is the energy absorbed (J), b is the width of the specimen(mm), and t is the thickness of the specimen (mm).

RESULTS AND DISCUSSION

Modulus of Rupture (MOR)

MOR is an essential standard of measuring the bending strength of materials. As shown in Fig. 4b, compared with the control group (with no glass fiber reinforcement), SGRS increased by 18.37%, 13.12%, 11.39%, and 8.4% for the four different density groups. This was because the contribution to bending modulus and toughness of the single glass fiber was higher than single poplar fiber. When the glass fiber was added in the poplar scrimber, totally combining with the poplar fiber, the local tensile strength of the specimen increased. Compared with the MOR of SGRS at the four density levels, the increase in amplitude of MOR of DGRS was smaller than which of SGRS. This happened because the bottom surface of the specimen withstood the highest tension and was the part that cracked first during the three-point bending test, so that the reinforcing glass fiber which was added into the third of thickness direction (close to the bottom surface) of the SGRS could help to increase the MOR more efficiently. In addition, when the density was increased, the MOR increasing percentage of the SGRS and DGRS were both decreased. This occurred because the proportion of reinforcing fiber decreased with the increased density. Compared with the MOR of DGRS, the MOR of TGRS decreased. This is because the enhancement of middle glass fiber reinforcement layer on the MOR of material is not obvious, in addition, it can also cause the delamination of the material.

According to the analysis of variance in the Table 2, the value of p of density and structure were both 0.00 which was smaller than 0.01, indicating that effects of density and structure on MOR were highly significant. The value of p of "density*structure" was 0.00 which was larger than 0.01, indicating that there was significant effect between the two factors.



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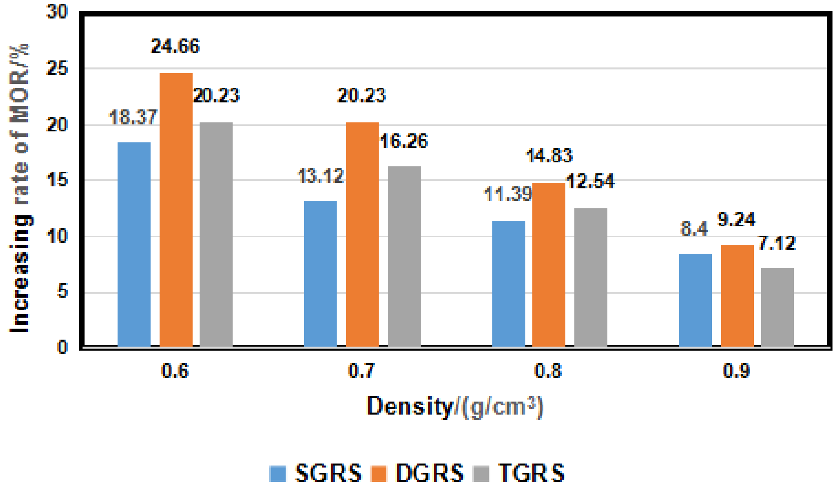


(b)

Fig. 4. (a) The MOR compared to the control for three types of reinforced scrimber and four density levels. (b) The increasing rate of MOR compared to the control for three types of reinforced scrimber and four density levels

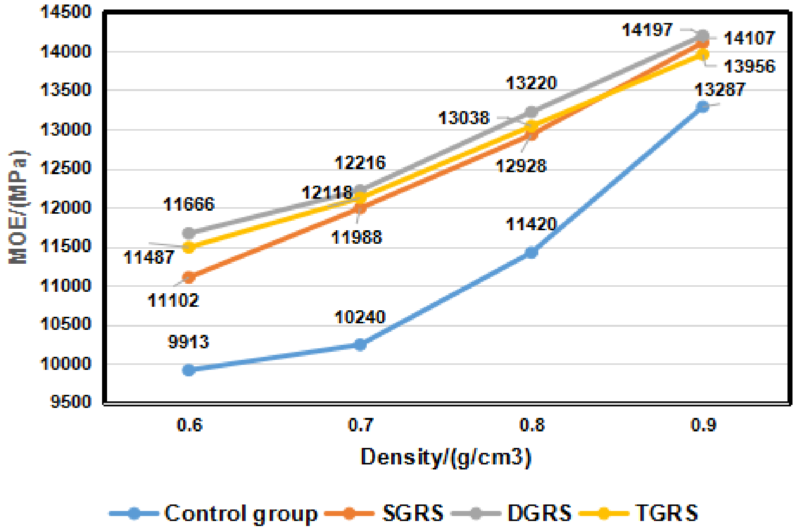
Table 2. Tests of Between-Subjects Effects of Density and Structure on MOR

Source	df	Mean Square	F-value	p
Corrected Model	15	658.403	48.503	0.000
Intercept	1	588481.230	43352.141	0.000
Density	3	1562.877	115.134	0.000
Structure	3	1211.310	89.235	0.000
Density*Structure	9	21.863	1.611	0.000
Error	48	13.574		
R-Squared = 0.973 (Adjusted R-Squared=0.917)				

Modulus of Elasticity (MOE)

As shown in Fig. 5b, the MOE of SGRS increased by 12%, 17.07%, 13.2%, and 6.17% at the four different densities compared with the control group. This can be explained by the better anti-bending strength and toughness of the glass fiber. Compared to the control group, the MOE of DGRS increased by 17.58%, 19.3%, 15.76%, and 6.85% at the four different densities. The MOE was the highest at 0.7g/cm^3. After 0.7g/cm^3, the MOE started to decrease. The MOE of TGRS decreased compared to the MOE of DGRS. This could be explained by the reason of MOR decreasing of TGRS.

According to the analysis of variance in the Table 3, the p-value of density and structure were both 0.00 which was smaller than 0.01, indicating that effects of density and structure on MOE were highly significant. The p-value of "density*structure" was 0.00 which was larger than 0.01, indicating that there was significant effect between the two factors.



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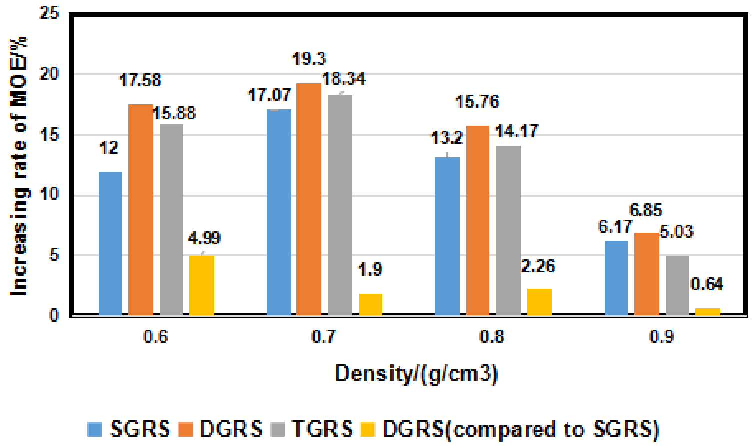


(b)

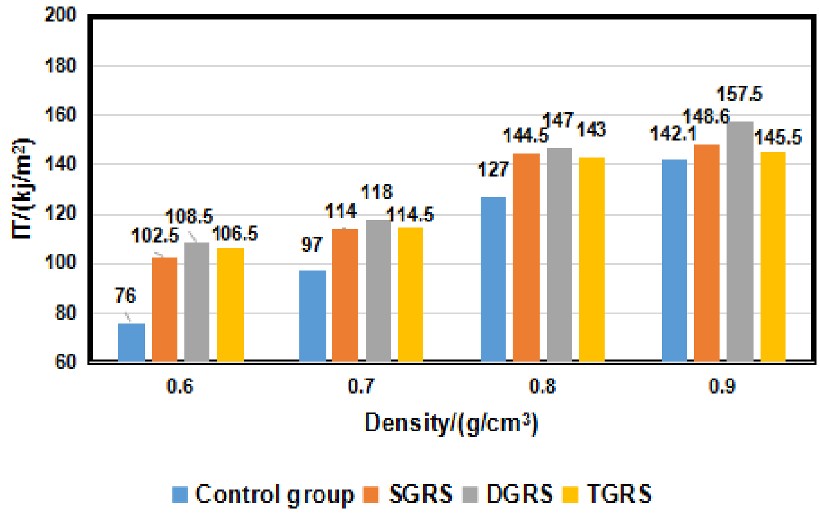
Fig. 5. (a) MOE in the control and three types of reinforced scrimber and four density levels. (b) The increase in MOE compared with the control for three types of reinforced scrimber and four density levels

Table 3. Tests of Between-Subjects Effects of Density and Structure on MOE

Source	df	Mean Square	F-value	p-value
Corrected Model	15	7855417.091	33.66	0.000
Intercept	1	7.132E9	30559.983	0.000
Density	3	20412672.44	87.466	0.000
Structure	3	11734527.00	50.281	0.000
Density*Structure	9	283752.778	1.216	0.000
Error	48	233378.00		
R-Squared = 0.911 (Adjusted R-Squared = 0.884)				

Impact Toughness

As Fig. 6b shows, the IT of the scrimber increased with increasing density.



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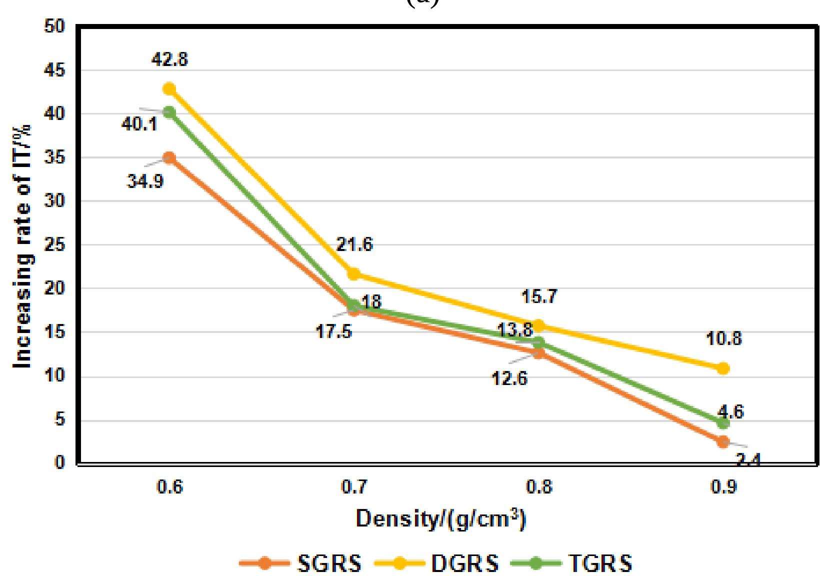


(b)

Fig. 6. (a) The IT impact toughness in compared with the control for three types of reinforced scrimber and four density levels, (b) the increasing rate of impact toughness IT compared with the control for three types of reinforced scrimber and four density levels

Compared with the control group, the IT of the SGRS increased by 34.9%, 17.5%, 13.8%, and 4.6%. This was because the toughness of the glass fiber was higher than the poplar fiber. At the same time, the glass fiber meshes achieved balance at the 0° and 90° directions, and the impact stresses were better distributed by cross-linked type through weaving together, increasing the fracture toughness of the specimen. Therefore, when the thickness direction plate withstood the transverse stress, the glass-fiber reinforced specimen distributed the stress more effectively. The IT of DGRS presented a weak increasing trend compared to the IT of SGRS; this is because the bottom of the specimen absorbed the most energy so that adding glass fiber was more efficient in dispersing stress. Compared to the IT of DGRS, the IT of the TGRS decreased slightly. This was because the enhancement effect provided by the middle glass fiber layer was very small, and the middle fiber layer can also cause the delamination of the materials.

At all the four density levels, the increasing rate of the IT of the scrimber was the highest at 0.6 g/cm^3. With the density increased, the increasing rate of the impact toughness presented a decreasing tendency. That can be explained by the adhesion power between fibers. At the low densities, the cell walls bind loosely, so the adhesion power between poplar fibers was much lower than the adhesion power between the glass fibers and poplar fibers. With the increasing of density, the adhesion power gap was reduced; therefore, the IT of fiber-reinforced scrimber at the low density increased more than the IT of high density fiber-reinforced scrimber.

According to the analysis of variance in Table 4, the p-value of density and structure were both 0.00 which was smaller than 0.01, indicating that effects of density and structure on IT were highly significant. The p-value of "density*structure" was 0.00 which was smaller than 0.01, indicating that there was significant effect between the two factors.

Table 4. Tests of Between-Subjects Effects of Density and Structure on IT

Source	df	Mean Square	F-value	p-value
Corrected Model	15	2157.965	139.405	0.000
Intercept	1	992464.251	64113.541	0.000
Density	3	9009.667	582.028	0.000
Structure	3	1499.044	96.839	0.000
Density*Structure	9	93.705	6.053	0.000
Error	48	15.48		
R-Squared = 0.973 (Adjusted R-Squared = 0.917)				

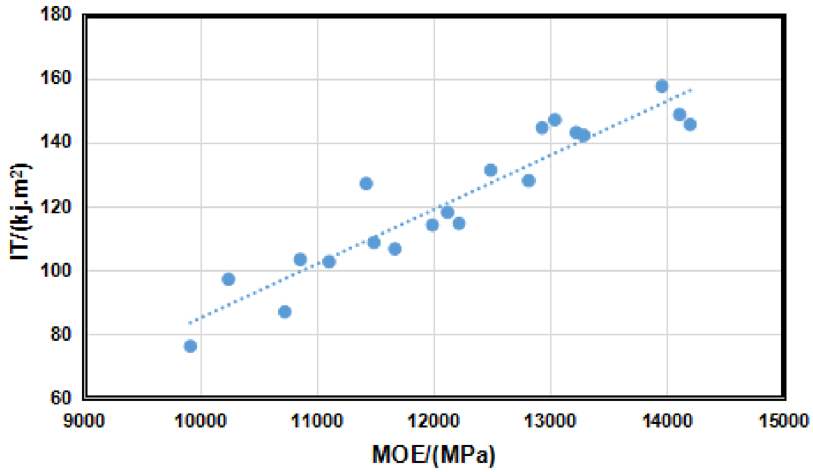
Linear Regression Analysis in Three Mechanical Properties of Glass Fiber Reinforced Scrimber

To analyze the correlation between the IT, MOE, and MOR, a relationship curve was developed (Fig. 5). The linear regression equation between IT and MOE was:

$$IT = 0.01908*(MOE) - 109.32 \qquad (1)$$

Because the linear regression coefficient of equation was $R = 0.7938 > R_{20,\,0.05} = 0.403$, there was an obvious linear correlation between IT and MOE. The linear regression equation between MOR and MOE was:

$$MOR = 0.0102*(MOE) - 14.802 \qquad (2)$$



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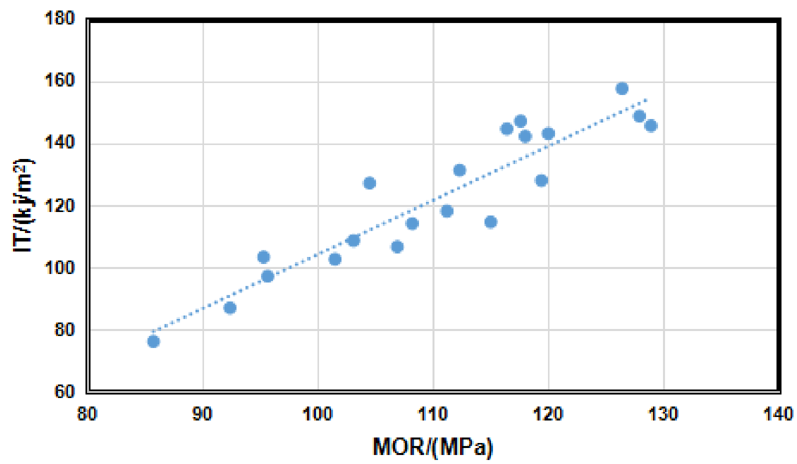

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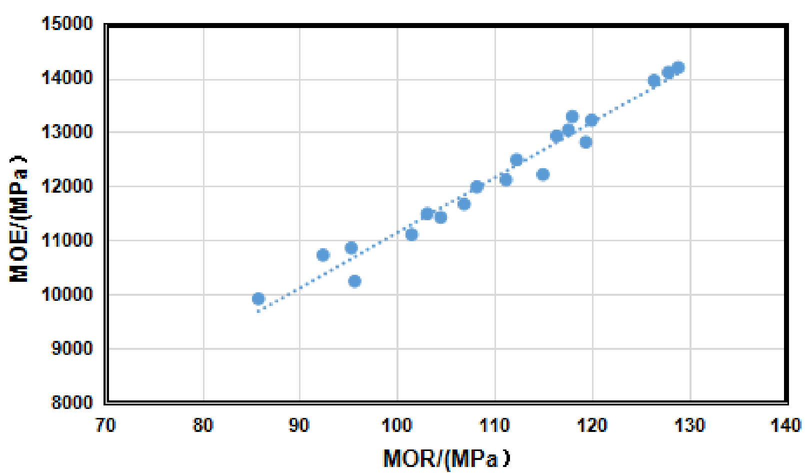

(c)

Fig. 7. (a) Linear regressions between IT and MOE, (b) Linear regressions between MOR and IT, (c) Linear regressions between MOR and MOE

There was an obvious linear correlation between MOR and MOE because the linear regression coefficient of equation was R = 0.8566 > $R_{20,\ 0.05}$ = 0.403. Meanwhile, the linear regression equation between MOR and IT was:

$$MOE = 42.533*(IT) + 6997.6 \quad (3)$$

There also was an obvious linear correlation between MOR and IT because the linear regression coefficient of the equation was R = 0.7893 > $R_{20,\ 0.05}$ = 0.403.

CONCLUSIONS

1. With the increase in the number of glass fiber mesh layers added in the fibrous scrimber, the MOR and MOE both increased at all density levels. The MOR and MOE of SGRS increased compared to the control group. The MOR and MOE of DGRS were increased, but the increase in amplitude was smaller than that of SGRS. Compared to the MOR and MOE of DGRS, the MOR and MOE of TGRS decreased slightly.
2. With increasing density, the rate of increase of the mechanical properties (MOR, MOE, IT) of the glass fiber reinforced scrimber showed a downward trend, indicating that the glass fiber had better effects on strength on the mechanical properties of the scrimber at low density(0.6g/cm^3,0.7g/cm^3).
3. The IT of SGRS and DGRS was increased compared to the control group. The IT of the DGRS reached the highest increasing rate compared to the control group; however, the IT of the TGRS decreased compared to the IT of DGRS impact toughness

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