Effect of Planar Preform Density on Mechanical Properties of Resin Transfer Molded Composites

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Abstract

The type and volume fraction of fibrous preform used in resin transfer molding has significant influence on the properties of the molded composite parts. In this study, effect of preform architecture and fiber volume fraction on the mechanical properties of resin transfer molded composites is experimentally investigated. A molding setup is constructed to fabricate center-gated, disk-shaped parts at constant flow rate. Two types of chopped, random glass-fiber preforms having different planar densities but otherwise similar structure are used. Molding is performed at three different fiber volume fractions, 9.8, 21.2, and 33.1 %, using both mat types. EPON 815C epoxy resin, mixed at 4.7:1 by volume with EPICURE 3282 curing agent, is used in order to obtain parts for mechanical characterization. Elastic modulus, tensile strength, and short beam shear strength are obtained by testing specimens cut from three locations within the molded parts.

Both stiffness and ultimate tensile strength are found to increase linearly with volume fraction. Experimental data show little change in the average tensile properties of disks having different mats at the same fiber volume fraction. However, slightly more variation in tensile properties is observed in individual specimens containing the higher density mats. Similarly, short-beam shear strength is found to be unaffected by the choice of thick or thin preforms at the volume fractions tested.

1- Introduction

Resin transfer molding (RTM) is a common process used to manufacture geometrically complex, medium to large composite parts. In RTM, a polymeric resin is injected under pressure into a mold cavity that contains a fibrous preform for reinforcement. A wide variety of resins and preform types can be selected based on the shape complexity, size, and performance requirements of the part. The ability to make complex and large parts at lower cost in relatively short time period is one of the advantages of RTM over other composite forming processes.

The mechanical performance of the resin transfer molded parts is influenced by many factors, including the mold geometry, fiber volume fraction [1-6], matrix properties [7], preform microstructure [8,9], resin-fiber interface [5,6,10,11], impregnation parameters [11], and void content [12]. Kang et al. [12], for instance, showed that in addition to void percentage, increase in the size and number of voids degrade mechanical properties. Matrix properties also influence overall part performance, as shown by Hine et al. who synthesized an improved matrix material that increased toughness and yield strength of reaction injection molded and resin transfer molded parts [7]. Pearce et al. [9], and Ericson and Berglund [8], among others, investigated the effect of changing fabric microstructure on properties, keeping fiber content constant.

It is well known that having higher fiber content enhances the mechanical performance of the composite parts. Simple rule of mixtures, or more advanced predictive models, such as those presented by Gao et al. [3] and Subramanian et al. [4], suggest linear increase in properties with fiber content for unidirectional composites. However under actual conditions there are upper limits on effectiveness of increased fiber content. For example, Lee and Jang observed decrease in tensile strength, flextural strength, and impact toughness above 20% fiber content for glass fiber reinforced compression molded composites [5]. They attributed the decrease in performance to higher measured void content and poorer fiber wetting observed in optical microscopy of high fiber volume fraction parts. Wang et al. avoided the reduction in properties at higher volume fractions by modifying the surface properties of the fibers for improved wetting [6]. They used catalytic grafting polymerization of ethylene on asbestos fibers to obtain improved properties at fiber contents up to 50%. Barraza et al. demonstrated inexpensive elastomeric sizings can be used to obtain properties comparable to those obtained using commercial sizings [10]. Patel et al. considered resin-fiber interface dependence on process parameters, by observing that lower injection rate and higher molding temperature result in better fiber wetting and bonding, thus increasing tensile strength [11].

In the RTM industry, random glass fiber preforms coated with commercial sizing (typically containing an organosilane coupling agent, film formers and lubricants) are commonly used because of their availability, lower cost, and planar isotropy. In the present study, preform architecture is varied by using two different types of glass fiber mats. Both mat types have similar random microstructure, but different planar densities and thus different thicknesses. Six series of disks are molded at the same process parameters using fiber volume fractions of 9.8, 21.2 and 33.1% for each preform type. For each of the six cases, test samples are cut from disk-shaped parts. Then tensile strength, short-beam shear strength, and elastic modulus are measured to determine the effect of mat type and fiber volume fraction.

When thin layers are used, effect of having additional layer interfaces on the tensile properties and short-beam shear strength is not known. However, one may expect to have similar properties at the same fiber volume fraction due to similar orientation structure if void content is not affected by the presence of additional layers. During the filling stage, the injection pressure is observed to be significantly lower for molds containing thin mats. Thus, if similar mechanical properties can be obtained at the same fiber content, it may be advantageous to use thin mats to lower the pressure requirements.

2- Experimental Setup

An experimental molding setup is constructed to fabricate resin transfer molded disks. The setup, depicted in Fig. 1, is composed of a molding press that injects a polymeric resin at constant flow rate and a disk-shaped mold cavity. The molding press contains two hollow cylinders, which are for resin and curing agent respectively. Plungers attached to the top plate of the press displace the resin and curing agent in the cylinders by equal distance when the top plate is pushed down. The flow from the two cylinders merges, and then passes through a Statomix style motionless inline mixer (Technical Resin Packaging, Inc.), which facilitates thorough mixing of the two components. The inline mixer is a polypropylene tube with an inside diameter of 5 mm, an outside diameter of 8 mm, and a length of 155 mm. Mixing is performed by 32 alternating helical segments inside the tube. The mixture is then injected into the center of the disk-shaped mold cavity. The force necessary to displace the plungers and inject the mixed resin is provided by a hydraulic press (ARCAN, 80 kip capacity). The hydraulic press moves at a constant velocity of $2x10^{-3}$ m/s, thus resulting in a constant injection rate.

The mold cavity, shown in Fig. 1, is constructed by placing a 3.18 mm (0.125 in.) aluminum spacer plate between two 6.35 mm (0.25 in.) thick aluminum mold walls. A 15.24 cm (6.0 in.) diameter circle is cut from the center of the spacer plate to form the disk-shaped cavity. After the filling takes place, holding a packing pressure on the mold has been demonstrated to produce higher quality parts [13]. In order to maintain pressure in the cavity, a 4 mm wide o-ring groove is machined into each mold wall to form a pressure tight seal. An inlet gate, positioned at the center of the disk-shaped cavity, is drilled and tapped for a hose fitting (ID=6.2mm) on the top mold wall. Four vents, positioned evenly around the cavity at a radius of 8.89 cm (3.5 in.), are also drilled and tapped for hose fittings in the top mold wall (ID=1.6 mm).

Depending on fiber volume fraction, molding times range between 6 and 9 seconds that are consistent with those expected in industrial molding of similar-sized parts. After filling, four vents hoses and the inlet hose are clamped sequentially to maintain the final fill pressure, and the part is left to cure in the mold for 48 hours before demolding. The part is then post cured at room temperature for a minimum of two additional weeks before the specimens are machined, polished, and tested to ensure complete development of properties.

Two different chopped-strand glass fiber mats having different planar densities i.e., thin mats with a planar density of 0.228 kg/m^2 (0.75 oz/ft^2, Fiberglast part #248), and thick mats with a planar density of 0.459 kg/m^2 (1.5 oz/ft^2, Fiberglast part #250), are used in this study. Both mat types have a randomly distributed, in-plane fiber orientation. Prior to filling, 15.24 cm (6.0 in.) diameter circles are cut from preforms and placed in the mold cavity to achieve desired fiber volume fraction. In this study, three fiber volume fractions are investigated (i.e., 9.8, 21.2, and 33.1 %). These fiber contents are achieved by placing 2, 4, or 6 layers respectively of the thick mats, or 4, 8, or 12 layers of the thin mats.

An epoxy resin, EPON 815C, manufactured by Shell Chemicals, is selected as the matrix material. Attractive properties of this resin include its low viscosity, which facilitates moderate injection pressures, and its low toxicity. The desired gel time of about 20 minutes is achieved by selecting EPICURE 3282 (Shell Chemicals) as the curing agent. EPON 815C and EPICURE 3282 are placed separately in two stainless steel cylinders. The internal diameters of these cylinders are machined to 55.47 mm and 25.53 mm in order to achieve the appropriate mix ratio, 4.7 to 1 by volume, of resin to curing agent. Cylinders contain enough resin and curing agent to mold six of the disks during a single stroke. Thus, six identical composite disks are fabricated in each molding session.

2.1- Tensile Test of Molded Composites

Each molded disk is cut into five 11.43x1.27x0.318 cm (4.50x0.50x0.125 in.) rectangular tensile test specimens in accordance with ASTM D3039/D3039M standard [14]. Figure 2 depicts the relative spatial positions of the five specimens within the molded disk. Angular orientation of the specimen array within each disk is arbitrary due to isotropic planar fiber orientation. Each disk yields a specimen (marked as 3 in Fig. 2) that contains the inlet gate at its center. Position 2 specimens are located symmetrically on either side of the center specimen, and position 1 specimens are at the edges of the disk as shown in Fig. 2. An aluminium template is used to hold the disk in place on a vertical milling machine so that specimens can be cut to the best tolerances possible. After the tensile specimens are cut, each specimen is polished with sandpaper to remove edge defects that might result in premature mechanical failure. A micrometer is used to measure each specimen thickness and width at five locations. Variations in the injection and post-fill pressure result in thickness variation between 0.3 and 0.4 cm among different samples.

Specimens at position 1 and 2 are tested under tension using the MTS machine at room temperature. Specimen at position 3 is not suitable for tensile testing due to possible defects induced by the inlet gate, where the cured resin column is broken off during demolding. During the tensile testing, the force is increased linearly from 0 to 8.90 kN (0-2000 lbs) over 120 seconds, however specimens typically fail at lower forces between 2.7 and 8.0 kN (600-1800 lbs), depending on fiber content and sample thickness. Strain is measured directly using an extensometer attached over a 2.54 cm (1.00 in.) span at the center of the specimen during testing. The stress is calculated by dividing the force by the cross sectional area, and stress-strain curves are generated for each specimen. Stress-strain curves have no distinct yield point and exhibit nearly linear behavior until failure. From the tensile data, maximum stress is obtained for each specimen, and elastic modulus is calculated over the linear region between 1000 and 3000 microstrain, as specified by ASTM D3039/D3039M.

2.2- Three-Point Bending Test of Molded Composites

Additional mechanical characterization of the parts is obtained by performing a three-point bending test in order to determine short-beam shear strength. Three-point bending test can be a good indicator of matrix-fiber adhesion and interlaminar shear strength. Testing is performed in accordance with ASTM D2344/D2344M standard for short-beam strength of high-modulus fiber-reinforced composite materials [15]. A number of position 1 specimen is cut into three 38.1 mm (1.5 in.) segments. The middle segment, which is symmetric about the radial line AA as shown in Fig. 2, is utilized for the three-point bending test. An adjustable three-point bend fixture, (MTS Series #642) is mounted on the MTS machine. The specimen is placed on two 3.175 mm (0.125 in.) diameter bottom rollers, adjusted to a center-to-center span of 25.4 mm (1 in.). A third roller, 6.35 mm (0.25 in.) in diameter, exerts force on the specimen center from above, moving down at a constant linear displacement of 1.27 mm/min. (0.05 in./min.). After failure, specimens are examined visually to ensure the failure mechanism is by shear, indicated by a white failure band through the thickness.

3- Results and Discussion

At least five disks are molded using each of the six preform configuration in order to obtain mechanical properties. All specimens from position 2 and half of the specimens from position 1 are tested under tension as described by ASTM D3039/D3039M. In a previous study of similar composite disks, tensile results were found to be statistically indistinguishable for positions 1 and 2 [16]. Thus data from these specimens are combined yielding at least 15 specimens for each data point to reduce statistical variation. A large number of specimens are used because random preforms have been shown to have large local variations in planar density [17] that leads to higher statistical variation in tensile results.

Measured values for ultimate tensile strength for each configuration are presented in Fig. 3. Strength values are plotted with error bars calculated using a 95% confidence interval. Tensile strength is observed to be equivalent within the range of statistical error for thick and thin mats at each of the three equivalent fiber volume fractions, with thick mats exhibiting slightly higher strengths at the lower two fiber volume fractions, and thin mats having slightly higher strength at highest fiber content. Both thick and thin mat strengths are observed to increase almost linearly with increasing fiber content, with 130% increase in strength for thick mats when fiber content is increased from 9.8% to 33.1%. Thin mats exhibit a 169% increase in strength over the same range of fiber content. For these six cases the uncertainty using the 95% confidence interval ranges between 7.5% and 18.2% with an average value of 13.4%.

Figure 4 contains corresponding data for elastic modulus for the six preform configurations, with error bars drawn again using a 95% confidence interval. Stiffness results are observed to follow trends similar to those exhibited by strength. The stiffness is found to be similar for thick and thin mats at the same fiber content, and increases linearly as fiber content is increased. Stiffness data, however, exhibit less improvement with increased fiber volume fraction, with only 100% increase in modulus between 9.8 and 33.1% fiber volume fraction. Stiffness data are found to have lower statistical variation, compared with tensile strength results with a range between 6.0% to 14.7% and an average value of 9.5%.

Three point bending test is also performed on molded parts to examine more subtle variations in mechanical properties introduced by additional layer interfaces for thin mats. It may be possible that these additional interfaces could weaken interlaminar shear strength of the composite material. A total of 5 tests are performed for each configuration. Measured short-beam shear strength values obtained from this test are presented in Fig. 5. Short-beam shear strength is observed to be similar for thick and thin mats at the same fiber content, with larger variation (7%) between mat types at 33.1% volume fraction. Although increase in shear strength is linear with volume fraction, thin mats exhibit the largest deviation in linearity of all mechanical data presented. This very slight deviation from linearity may be attributed to higher statistical variations of planar preform density, particularly at lower fiber content. At lower fiber content, variations in mats are less likely to even out over smaller number of layers, thus leading to higher property variations.

4- Concluding Remarks

Results are presented demonstrating effect of fiber volume fraction and planar preform density (i.e., mat thickness) on mechanical properties of resin transfer molded composites. At same fiber content, planar preform density has negligible effect on mechanical properties, demonstrated by comparable values for elastic modulus, tensile strength, and short-beam shear strength. Mechanical properties are observed to increase linearly between 9.8% and 33.1% fiber volume fraction. Average increase of about 150% for ultimate tensile strength is observed, while stiffness and short-beam shear strength exhibit a slightly lower improvement of 100% over the same volume fraction range. Considering that, at a given fiber volume fraction, thinner mats require lower injection pressure compared to thick mats, it may be beneficial to use thin mats to achieve the desired mechanical performance.

5- References

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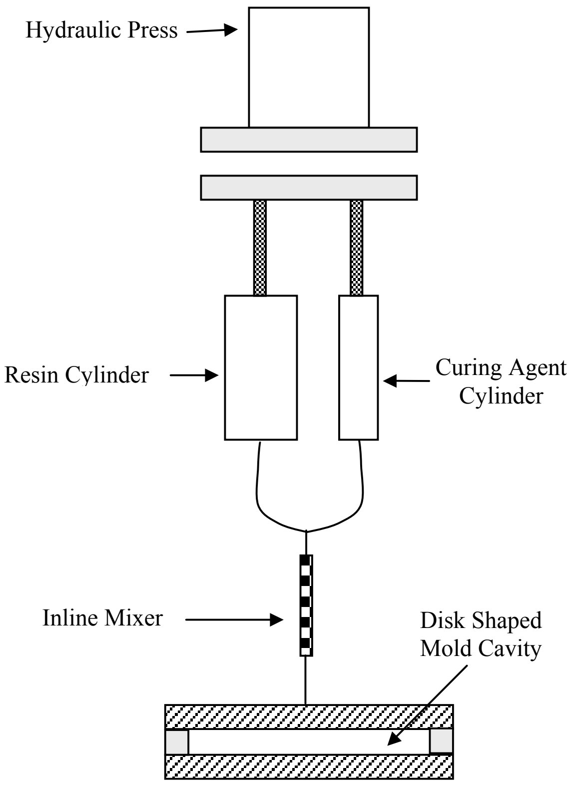

Figure 1 – Experimental setup used to fabricate resin transfer molded disks.

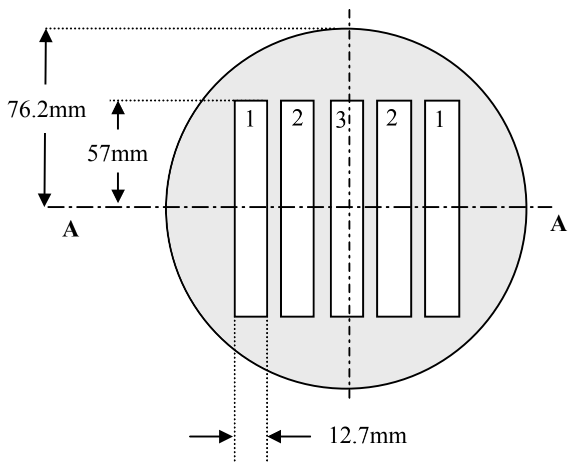

Figure 2 – Spatial arrangement of five tensile test specimens in a molded disk.

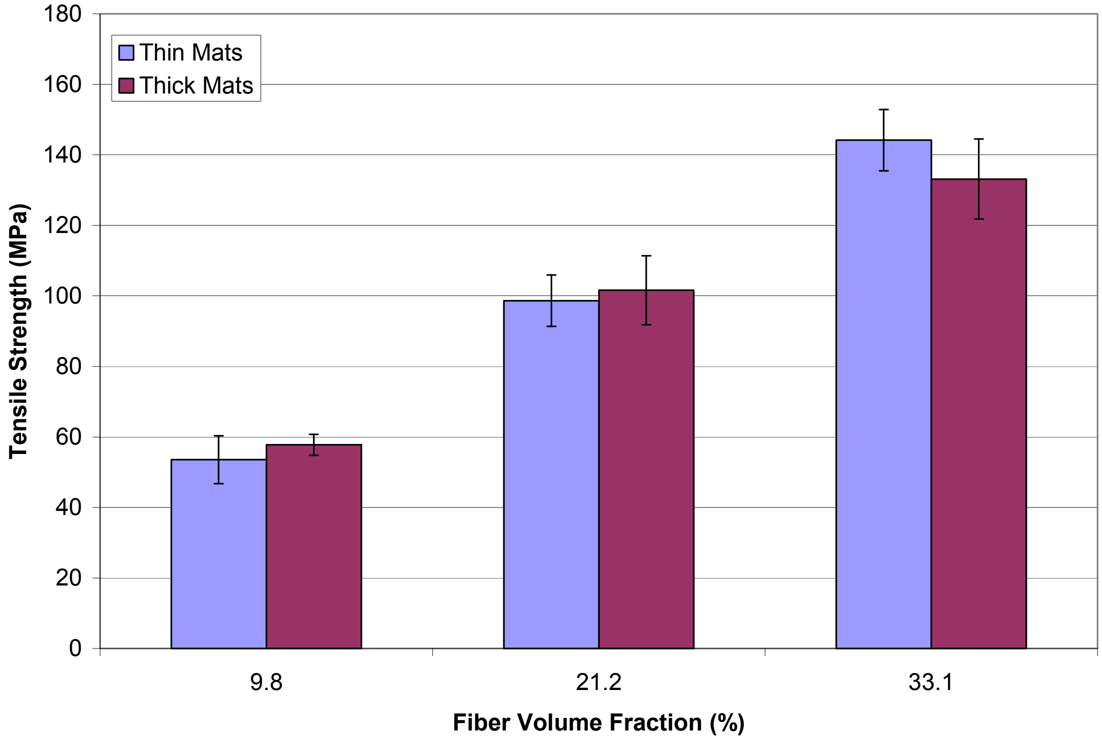

Figure 3 – Ultimate tensile strength of molded composites with thick and thin mats at three fiber volume fractions.

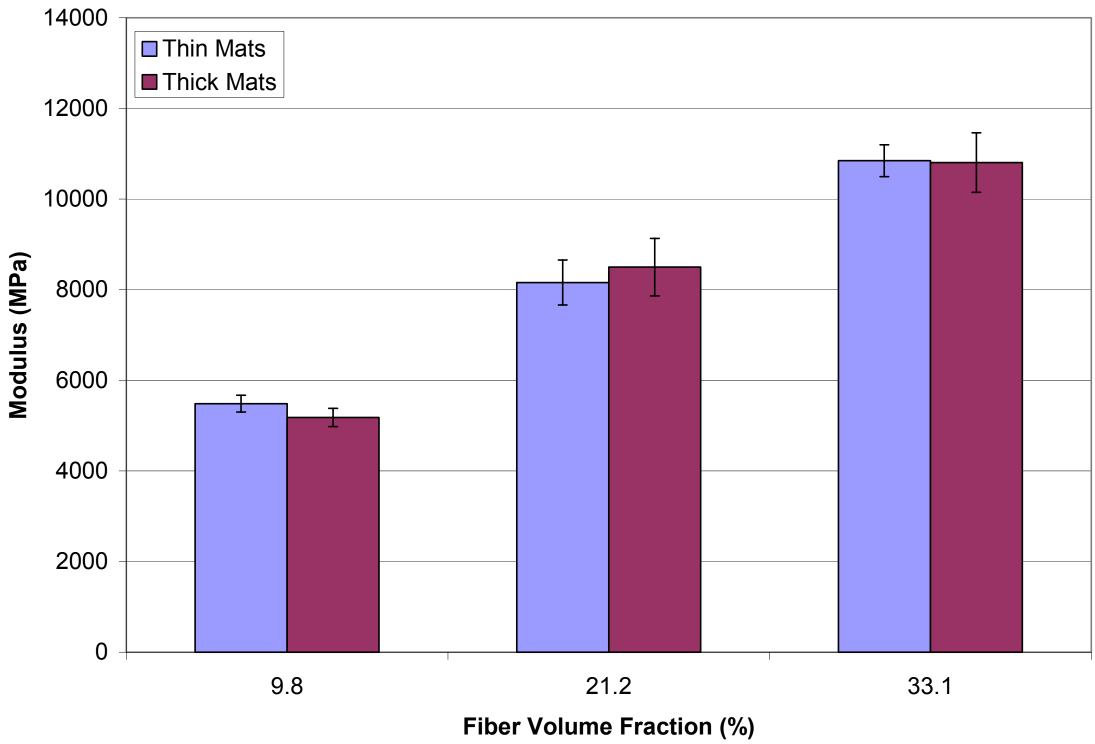

Figure 4 – Elastic modulus of molded composites with thick and thin mats at three fiber volume fractions.

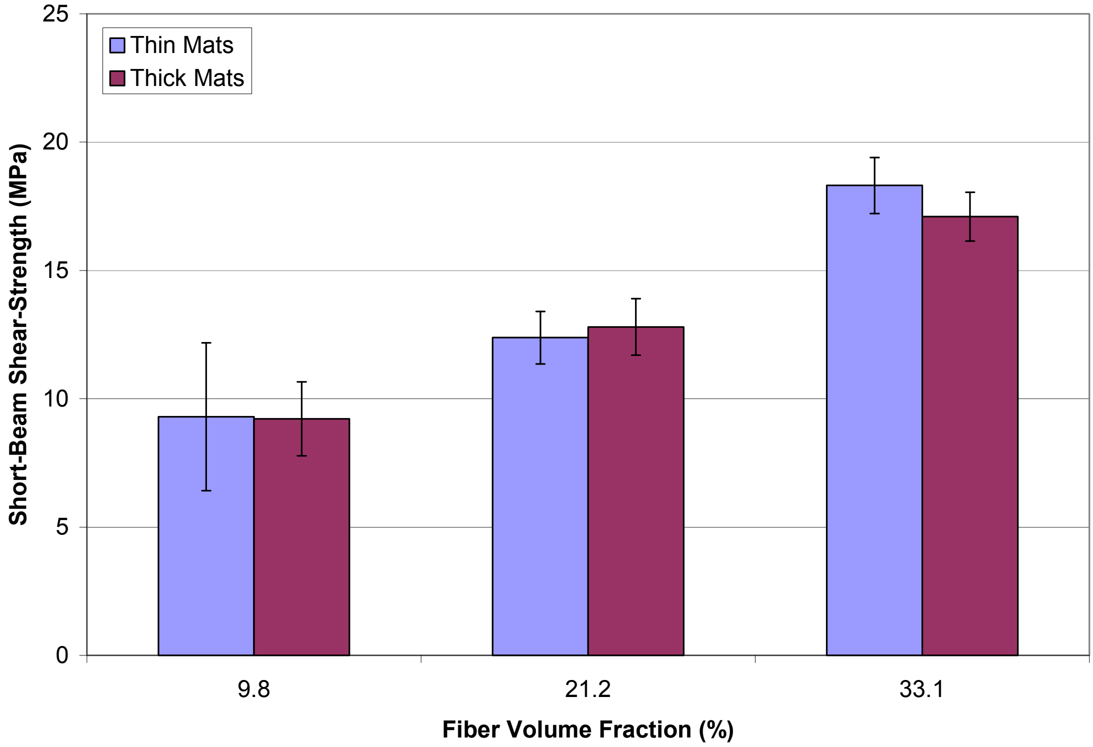

Figure 5 – Short-beam shear strength of molded composites with thick and thin mats at three fiber volume fractions.