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Mechanical Properties of Woven Glass Fiber-Reinforced Composites

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The aim of this investigation was to measure the flexural and compressive strengths and the corresponding moduli of cylindrical composite specimens reinforced with woven glass fiber. Test specimens were made by light-curing urethane dimethacrylate oligomer with woven glass fiber of 0.18-mm standard thickness. Tests were conducted using four reinforcement methods and two specimen diameters. Flexural strength and modulus of woven glass fiber-reinforced specimens were significantly greater than those without woven glass fiber ($p<0.01$). Likewise, compressive strength of reinforced specimens was significantly greater than those without woven glass fiber ($p<0.01$), except for specimens reinforced with woven glass fiber oriented at a tilt direction in the texture ($p>0.05$). In terms of comparison between the two specimen diameters, no statistically significant differences in flexural strength and compressive strength ($p>0.05$) were observed.

Key words: Mechanical property, Glass fiber, Composite

INTRODUCTION

Of late, fueled by increasing demands for esthetic restorations, glass fibers are likewise widely used for reinforcement of dental restorative materials. This is because glass fibers have excellent transparency and can bond chemically to dental polymers − such as methyl methacrylate, Bis-GMA, or UDMA − by silanization. In clinical applications, post and core resin composites are increasingly being reinforced by glass fibers. Against this background, Mannocci *et al.*[1], Lassila *et al.*[2], and Grandini *et al.*[3] measured the flexural strength of various commercial fiber posts. On the same trail to find out more about the influence of glass fiber-reinforced posts and cores, Innella *et al.*[4] reported on the relation between insertion length and post retention, while Yoldas and Alaçam[5] studied the curing depth of composites using light transmitting posts and glass-fiber reinforced composite posts. Besides, Kishita *et al.*[6] investigated the feasibility of applying glass fiber-reinforced composites to clasps by performing strength test with repeated loading. Then, there were also other trial investigations[7−10] for orthodontic wires and fixed partial dentures. At this juncture, it should be highlighted that glass fiber-reinforced composite materials are often used with a cylindrical shape, and that any attempt to add force directions so as to improve strength for clinical use will be a very complicated undertaking.

In cases where composites are reinforced with woven glass fiber, the content, position, and direction of fibers may affect the mechanical properties of the composite. Dyer *et al.*[11] studied the effects of fiber position and orientation on fiber-reinforced composites, and reported that these two factors influenced the loads to initial and final failures, as well as specimen deflection. In that investigation, square specimens were used and the dimensions of all specimens examined were identical. The aim of this investigation, however, was to measure the flexural and compressive strengths of cylindrical woven glass fiber-reinforced composites with different diameters and woven glass fiber contents.

MATERIALS AND METHODS

Woven glass fibers (YETH18050, Mie Fabrics, Mie, Japan) of 50-mm width and 0.18-mm standard thickness, and with a plane weave texture and E-glass composition, were used for woven glass fiber reinforcement. After the woven glass fibers were boiled in water for one hour, they were air-dried for one day. On the following day, the woven glass fibers were soaked in a solution of 2% γ-methacryloxypropyltrimethoxysilane (Shinetsu Chemicals, Tokyo, Japan) in ethanol for 10 minutes to achieve silanization. Then, the woven glass fibers were air-dried for one hour and heated in an oven at 115℃ for one hour. Silanized woven glass fibers were cut into 9-, 12-, 20-, and 40-mm lengths. The cut edge was painted with an oligomer mixture, which was light-cured so that the woven glass fiber would not fray. The oligomer mixture was composed of an urethane dimethacrylate oligomer (SH-500B, Negami Chemical Industries, Ishikawa, Japan) containing 1 wt% camphorquinone (Wako Pure Chemical Industries Ltd., Osaka, Japan) as a photosensitizer and 1 wt% 2-dimethylaminoethyl methacrylate (Wako Pure Chemical Industries Ltd., Osaka, Japan) as a reductant.

Each treated woven glass fiber was wound to a plastic rod with 1-mm diameter, which was fitted into a fluorocarbon resin tube with 4-mm inner diameter (for codes 4-O, 4-I, 4-F, and 4-T) and with 3-mm inner diameter (for codes 3-O and 3-F) as shown in Table 1. After the plastic rod was carefully pulled out, one end of the resin tube was dipped into the oligomer mixture and other end was vacuumed so as to be filled with the oligomer mixture without air bubbles. The filled tube was light-cured using an irradiation unit (α-Light, Morita Corporation, Tokyo, Japan) for five minutes. The cylindrical composites were pulled out from the tube and cut into 40-mm length for flexural test specimens and 10-mm length for compressive test specimens using a water-cooled diamond blade (Fig. 1).

Mechanical properties measurement

A three-point flexural test was conducted with a universal testing machine (TG-50kN, Minebea, Nagano, Japan) using a crosshead speed of 2 mm/min and a span length of 30 mm. A compression test was also conducted with a crosshead speed of 0.5 mm/min. Flexural strength (F_S) and modulus (F_m), as well as compressive strength (C_S) and modulus (C_m), were calculated using the following formulas:

$$F_S=\frac{8SP}{\pi D^3} \qquad F_m=\frac{4S^3P_l}{3\pi BD^4}$$

$$C_S=\frac{4P}{\pi D^2} \qquad C_m=\frac{4LP_l}{\pi BD^2}$$

where P is the maximum load, P_l is the load within the proportional limit, B is the displacement within the proportional limit, S is the span length (30 mm), and L and D are the length and diameter of the test specimens respectively.

Woven glass fiber content

Three specimens of each code for the compression test were measured with a micrometer for their dimensions and then fired in a porcelain crucible at 600 ℃ for six hours. The woven glass fiber, a residue after incineration, was reweighed (W_g) after cooling down to room temperature. The percentage of woven glass fiber content by volume (V_g vol%) was calculated with the following formula:

$$V_g=(W_g/r_g)/V_a$$

where V_a (cm^3) is the specimen volume before firing and r_g is the density of woven glass fiber (2.50 g/cm^3)[3].

Statistical analysis

From every group, five specimens were used for each test. Test specimens of 4-mm diameter but without woven glass fiber were made by the same method to act as controls (4-N). One-way analysis of variance (ANOVA) and Tukey's test were used to compare the differences in mechanical properties.

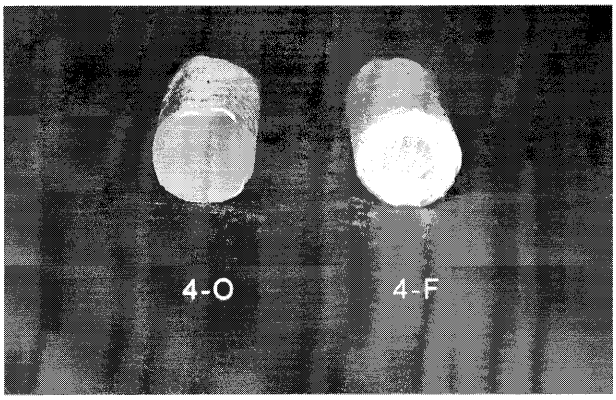
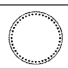
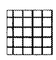
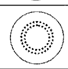
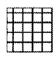
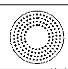
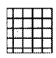
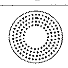
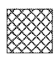
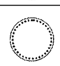
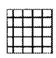
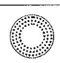
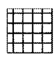


Fig. 1 Samples of test specimens used in this investigation (left: 4-O; right: 4-F).

Table 1 Specimen codes, conditions of test specimens, and woven glass fiber contents

Code	Specimen		Woven glass fiber		
	Cross section	Diameter (mm)	Length (mm)	Texture	Content (vol%)
4-O		4	12		8.6
4-I		4	12		8.6
4-F		4	40		28.8
4-T		4	40		25.5
3-O		3	9		11.5
3-F		3	20		26.2

RESULTS

Table 2 shows the flexural and compressive strengths, and their corresponding moduli.

Flexural strengths and moduli of 4-O, 4-I, 4-F, 4-T, 3-O, and 3-F were significantly greater than those of 4-N ($p<0.01$). Between 4-O and 4-I, there were no statistical differences ($p>0.05$) in both flexural strength and modulus. Conversely, between 4-F and 4-T, high statistically significant differences ($p<0.01$) in both flexural strength and modulus were found. Between the two specimen diameters (3 and 4 mm), there were no statistically significant differences ($p>0.05$) in flexural strength, but a statistical difference ($p<0.01$) was found in flexural modulus.

Compressive strengths of 4-O, 4-I, 4-F, 3-O, and 3-F were significantly greater than that of 4-N ($p<0.05$), while the compressive moduli of 4-F, 3-O, and 3-F were significantly greater than that of 4-N ($p<0.01$). Between 4-O and 4-I or between 4-F and 4-T, the effect of woven glass fiber on compressive strength and modulus displayed a similar tendency to that observed for flexural test. But between the two specimen diameters (3 and 4 mm), no statistically significant differences ($p>0.05$) were found.

Woven glass fiber contents of 4-O, 4-F, 3-O, and 3-F were 8.6, 28.8, 11.5, and 26.2 vol% respectively (Table 1). The correlation between woven glass fiber content and flexural or compressive strength are shown in Figs. 2 and 3 respectively. The correlation coefficients for flexural strength and compressive strength were 0.967 and 0.961 respectively. Relationship between flexural strength and compressive strength is shown in Fig. 4, which was a linear relation with $r=0.87$.

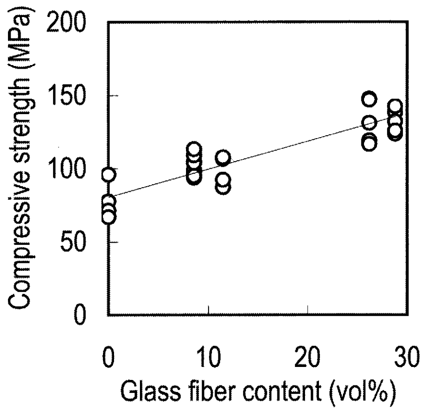


Fig. 3 Correlation of compressive strength and woven glass fiber content.

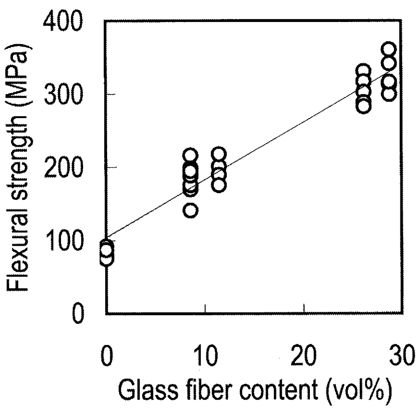


Fig. 2 Correlation of flexural strength and woven glass fiber content.

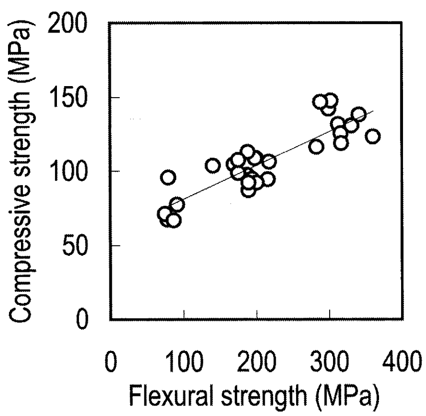


Fig. 4 Correlation of flexural strength and compressive strength.

Table 2 Mean values and standard deviations of flexural strength and modulus, and compressive strength and modulus

Code	Flexural		Compressive	
	Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)
4-N	82.6(6.8)	1.39(0.13)	75.7(11.9)	1.70(0.15)
4-O	185.0(12.4)	4.83(0.41)	100.7(6.1)	2.60(0.45)
4-I	187.6(28.2)	4.47(0.70)	103.0(8.3)	2.66(0.38)
4-F	326.1(24.5)	9.80(0.89)	132.3(8.0)	4.01(0.03)
4-T	186.3(15.4)	6.53(0.40)	71.5(2.8)	2.59(0.50)
3-O	194.7(15.8)	6.15(0.50)	97.1(9.2)	3.54(0.01)
3-F	304.4(19.9)	11.4(0.47)	132.1(14.8)	5.59(1.48)

SD in parentheses

DISCUSSION

The flexural strength of all reinforced specimens was significantly greater than that of non-reinforced specimens ($p<0.01$). Load-deflection curve of 4-F showed the same breaking mechanism as the stepwise, statistical failure reported by Dyer *et al.*[11]. At load of about 160 N (Fig. 5), the knee point was observed and microfracture could be introduced by drawing of glass fiber, or drawing or breaking of resin matrix. In the mean time, interfacial fracture existed between the glass fiber and resin until about 190 N (Fig. 5). However, the curve changed to somewhat like the teeth of a saw (B curve shown in Fig. 1 by Dyer *et al.*[11]) when load exceeded 190 N and kept on increasing. In a previous study[12], we reported that when three-point flexural test was conducted using square specimens, the greatest tension occurred at the outermost position of the fiber-reinforced polymer. In the present study, when the load was applied to cylindrical specimens in the three-point flexural test, tension occurred within the lower half cross-section of the specimens — *i.e.*, the opposite side of the point of applied force. Hence, the outermost glass fiber in the cylindrical specimens sustained the largest tension and held the key to showing the first signs of fiber failure.

Although 4-O and 4-I observed no statistical differences ($p>0.05$) in flexural strength, they showed different load-deflection curves (Fig. 5). The knee points for 4-O and 4-I were at about 60 and 120 N load respectively (arrows in Fig. 5). At the knee point for 4-O, woven glass fiber of the outermost position might break first; however, woven glass fiber at the side positions would resist breaking continually as failure progressed till catastrophic fracture occurred.

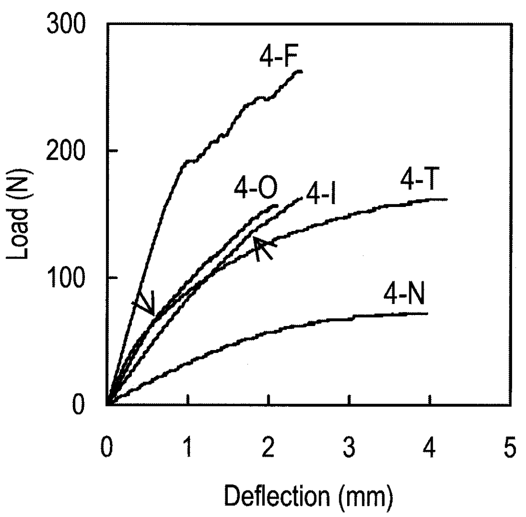


Fig. 5 Load-deflection curves obtained from the three-point flexural test.

Among 4-F with vertical fiber direction, 4-T with tilt fiber direction, and 4-N of control, statistical differences ($p<0.01$) were apparently observed in flexural strength (Fig. 5). However, no statistical differences ($p>0.05$) were observed between 4-T and 4-N in compressive strength. While the woven glass fiber of horizontal direction resisted the extension of a circular cross-section with a cylindrical polymer specimen caused by a compressive load in compression test, the woven glass fiber of tilt direction showed little effect. It has been shown by Fennis *et al.*[13] through fracture resistance test that woven glass fiber-reinforced composite (FRC) cusp-replacing restorations did not increase the fracture load of premolars; however, woven glass fibers gave more consistent results than unidirectional fibers. The present study and that by Fennis *et al.*[13] served to illustrate the effect of woven glass fibers of the same direction against the line of applied load. Hence, it was suggested that it would be effective to use prepolymerized cylindrical composites reinforced with woven glass fiber for molar restorations or resin core constructions, as they not only strengthen but also decrease polymerization shrinkage. Nonetheless, further testings and evaluations are needed in this respect.

From Figs. 2 and 3, it could be seen that flexural strength and compressive strength increased as the woven glass fiber content increased. Braem *et al.*[14] studied the relationship between mechanical properties and filler fraction, and reported 1.1-times increase in transverse strength using square specimens with woven glass fiber content of 28.6 vol%. In the present study, flexural strength and compressive strength of composite specimens with 28.8 vol% of woven glass fiber increased 3.9-times and 1.7-times respectively. This tendency was likewise observed in test specimens with different diameters, because there were no statistically significant differences in flexural strength and compressive strength between 4-O and 3-O, and between 4-F and 3-F (Table 2). The cylindrical composite specimen was clearly strengthened by the addition of woven glass fiber, and the strength increased as the woven glass fiber content increased.

Glass fiber posts have been the preferred choice because of these key advantages: elastic modulus is similar to that of dentin, strong adhesiveness to resin cement or core resin, excellent esthetic results with all-ceramic crowns, and easily removable. Lassila *et al.*[2] examined the flexural properties of various commercial fiber posts, and reported 560.0-902.2 MPa and 13.5-20.8 GPa for flexural strength and modulus respectively. In the present study, the flexural strength and modulus ranged from 185.0 to 326.1 MPa and from 4.47 to 11.4 GPa respectively — and these values were smaller than those of commercial products. These discrepancies in flexural data could be attributed to the vast differences in quality and texture between the unidirectional glass fibers used for the commercial fiber posts versus the woven glass fibers used in this investigation. In the present research, a urethane oligomer without filler was used as the matrix resin to serve the purpose of clarifying the reinforcement effect of woven glass fiber. In the electrical industry, it is recognized that printed wiring boards reinforced with woven glass fiber and globular filler will lead to an increase in flexural modulus[15]. Furthermore, it is known that mechanical properties can be enhanced by adding more inorganic filler. Based on these given concerns, any increase in the flexural properties of the presently examined woven glass fiber-reinforced composite should be accomplished by a matrix resin containing inorganic filler.

As seen in Fig. 4, there was a linear relation ($r=0.87$) between flexural strength and compressive strength for all test specimens except 4-T. The ratios of 4-O/4-N in flexural and compressive strengths were 2.2 and 1.3, while those of 4-F/4-N were 3.9 and 1.7, respectively. For flexural and compressive moduli, the ratios of 4-O/4-N were 3.5 and 1.5 respectively, while those of 4-F/4-N were 7.1 and 2.4 respectively. Though the weft yarn is effective for compressive strength, the results clearly indicated that the woven glass fiber affected the flexural properties more than the compressive properties. Narva *et al.*[16] investigated the fatigue resistance and stiffness of unidirectional glass fiber-reinforced composites using cylindrical test specimens, and concluded that reduction in flexural modulus of fiber-reinforced composites may restrict their use where high rigidity is required. Within the limitations of this study, it was shown that the addition of woven glass fibers increased the flexural and compressive properties of cylindrical composite specimens. These results indicated that the position and direction of glass fibers is important for reinforced composites, and that it is necessary to use the glass fibers that meet the objectives of each application especially in terms of loading force.

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