Acta Odontologica Scandinavica. 2015; 73: 581–587

informa
healthcare

ORIGINAL ARTICLE

Flexural properties of polyethylene, glass and carbon fiber-reinforced resin composites for prosthetic frameworks

YUKINORI MARUO[1], GORO NISHIGAWA[1], MASAO IRIE[2], KUMIKO YOSHIHARA[3] & SHOGO MINAGI[4]

[1]*Department of Occlusion and Removable Prosthodontics, Okayama University Hospital, Okayama, Japan,* [2]*Department of Biomaterials, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama, Japan,* [3]*Center for Innovative Clinical Medicine, Okayama University Hospital, Okayama, Japan, and* [4]*Department of Occlusal and Oral Functional Rehabilitation, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama, Japan*

Abstract

Objective. High flexural properties are needed for fixed partial denture or implant prosthesis to resist susceptibility to failures caused by occlusal overload. The aim of this investigation was to clarify the effects of four different kinds of fibers on the flexural properties of fiber-reinforced composites. ***Materials and methods.*** Polyethylene fiber, glass fiber and two types of carbon fibers were used for reinforcement. Seven groups of specimens, 2 × 2 × 25 mm, were prepared ($n = 10$ per group). Four groups of resin composite specimens were reinforced with polyethylene, glass or one type of carbon fiber. The remaining three groups served as controls, with each group comprising one brand of resin composite without any fiber. After 24-h water storage in 37°C distilled water, the flexural properties of each specimen were examined with static three-point flexural test at a crosshead speed of 0.5 mm/min. ***Results.*** Compared to the control without any fiber, glass and carbon fibers significantly increased the flexural strength ($p < 0.05$). On the contrary, the polyethylene fiber decreased the flexural strength ($p < 0.05$). Among the fibers, carbon fiber exhibited higher flexural strength than glass fiber ($p < 0.05$). Similar trends were observed for flexural modulus and fracture energy. However, there was no significant difference in fracture energy between carbon and glass fibers ($p > 0.05$). ***Conclusion.*** Fibers could, therefore, improve the flexural properties of resin composite and carbon fibers in longitudinal form yielded the better effects for reinforcement.

Key Words: *Flexural property, polyethylene fiber, glass fiber, carbon fiber, resin composite*

Introduction

In today's dental prosthetic treatments, fixed partial dentures and implant-supported prostheses must meet many functional and esthetic needs: preserve underlying residual oral tissues, restore masticatory ability and maintain phonation and esthetic appearance [1]. Ceramics or resin composite materials could overcome metal allergies or inferior esthetic outcome caused by the conventional prostheses made with metal alloys [2,3].

Resin composites are widely used as a dental restorative material because of these advantages: biocompatible with oral tissues, easily manipulated into various design configurations and highly esthetic. However, they have lower flexural strength than metal alloys [4,5], rendering them susceptible to failures caused by occlusal disharmony, overload, fatigue, abrasion and attrition [1].

While the final restoration is being made and until it is administered, provisional restorations made of resin composites represent an important element of dental prosthetic treatments: they support the teeth and provide proper occlusal function [6]. To ensure long-term success, resin composites must have high flexural strength, high elastic modulus, low deformation, as well as high impact and fatigue resistance to withstand the effects of masticatory and thermal stresses in the mouth. Resin composites used to be reinforced by metal wires and plates to achieve

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Correspondence: Dr Yukinori Maruo, Department of Occlusion and Removable Prosthodontics, Okayama University Hospital, 2-5-1, Shikata-cho, Okayama 700-8525, Japan. Tel: +81 86 235 6687. Fax: +81 86 235 6689. E-mail: ykmar@md.okayama-u.ac.jp

(Received 5 June 2014; accepted 8 August 2014)

ISSN 0001-6357 print/ISSN 1502-3850 online © 2015 Informa Healthcare

DOI: 10.3109/00016357.2014.958875

superior mechanical properties [7,8]. However, metal-reinforced composites are neither manipulable nor esthetically pleasing for a wide range of dental applications [9].

Fibers have been used to reinforce composites in engineering applications to improve their mechanical properties [9]. To circumvent the problems associated with metal-reinforced composites, fibers were used to reinforce denture base resins [10–13]. The mechanical behavior of fiber-reinforced resin composites is complex, with their properties ranging from isotropic to anisotropic and heavily influenced by the type, volume, location, and direction of the fibers [14–16]. In dentistry, continuous and long fibers located at the tensile side of prosthetic appliances, with strands perpendicular to the direction of applied load, were found to favor the reinforcement of resin composites [9,14].

Glass and polyethylene fibers are used not only to enhance the mechanical properties of resins, but also for their good esthetic attributes, good biocompatibility, and easy manipulability in the clinic or dental laboratory [17–20]. With glass fibers, the bond strength to resins could be markedly improved using silane coupling agents [20,21]. For these reasons, glass and polyethylene fibers have become very popular in recent years [6].

Although carbon fibers are superior to glass and polyethylene fibers in increasing the mechanical properties of resin composites, they pose an esthetical disadvantage by virtue of their black appearance. This is the main reason why carbon fibers have not become popular in the dental field. Nonetheless, the black appearance of carbon fibers can be masked by an opaque resin layer, yielding the same esthetic outcome as glass and polyethylene fibers.

In the present study, polyethylene, glass or carbon fibers were added to commercially available resin composites used for dental prosthetic frameworks. The aim of this study was to assess and compare the effects of these fibers on flexural strength, flexural modulus and fracture energy, based on the hypothesis that fiber reinforcement would increase both flexural strength and modulus of resin composites.

Materials and methods

Types of fibers and resin composites

For polyethylene and glass fibers, two commercially available fiber-reinforced systems were selected for this study: polyethylene fiber-reinforced composite, Construct (Kerr, Orange, CA) and glass fiber-reinforced composite, Estenia C&B EG Fiber (Kuraray Medical,

Table I. Materials used in this study.

Materials	Brand names	Ingredients	Batch no.	Manufacturer
Resin composite	Construct resin (NAT)	Ethoxylated bisphenolAdimethacrylate/ Camphoroquinone/Silicon dioxide	2888511	Kerr, Orange, CA
	Estenia C&B EG flow	Monomer [Urethane dimethacrylate, TEGDMA, other methacrylate monomer]/Photopolymerization catalyst/ Tinction	0012JA	Kuraray Medical, Tokyo Japan
	Clearfil DC core automix (Dentine)	Catalyst [Monomer (Bis-GMA, TEGDMA)/Filler (Surface treatment glass powder, Surface treatment silica microfiller)/Photopolymerization catalyst/ Chemical polymerization catalyst/ Tinction] Universal [Monomer (TEGDMA, other methacrylate monomer)/Filler (Surface treatment glass powder, Surface treatment silica microfiller)/Photopolymerization catalyst/Chemical polymerization catalyst/ Tinction]	00084A	Kuraray Medical, Tokyo Japan
Polyethylene fiber	Construct (1 mm)	Polyethylene/Ethoxylated bisphenolAdimethacrylate	2925762	Kerr, Orange CA
Glass fiber	Estenia C&B EG fiber (for Anterior)	Monomer [Urethane dimethacrylate, TEGDMA, other methacrylate monomer]/Surface treatment glass fiber/ Surface treat microfiller/ Photopolymerization catalyst/Tinction	00021B	Kuraray Medical, Tokyo Japan
Carbon fiber	Torayca (T300B-3K-50B, T700SC-12K-50C)	Des not provide the detail The number filament of 3K and 12K is 3,000 and 12,000, respectively	Does not provide	Toray, Tokyo, Japan

Figure 1. Types of fibers used to reinforce resin composites in this study: (A) Polyethylene fiber; (B) Glass fiber; and (C) Carbon fiber.

Tokyo, Japan). Two types of carbon fibers selected for this study were Torayca T300B-3K-50B and T700SC-12K-50C (Toray, Tokyo, Japan), which had 3,000 and 12,000 carbon filaments per fiber, respectively. Details and photographic images of these different types of fibers are presented in Table I and Figure 1.

For matrix resin, three commercial brands of resin composites were selected for this study (Table I).

Specimen preparation

Seven groups of specimens were prepared in this study, with 10 specimens per group. Four groups of resin composite specimens were reinforced with polyethylene, glass or one type of carbon fiber. The remaining three groups served as controls, with each group comprising one brand of resin composite without any fiber.

A Teflon split mold (2.0 mm depth, 2.0 mm width and 25 mm length) was used to prepare the specimens. All specimens were prepared for flexural strength measurement and a Teflon split mold would minimize the stresses exerted on the specimens during their retrieval.

The mold was filled with material, covered with a plastic strip and glass plate and clamped. After 20 s, the glass plate was removed. Specimen was light-cured for 5 min using a light curing unit (Labolight LV-II, GC, Tokyo, Japan). After the specimen was removed from the mold and excess material was removed, the specimen was polished with sandpaper (#600, Struers A/S, Rodovre, Denmark) to obtain smooth and flat surfaces. Specimen dimensions were measured using a digital micrometer (No. 293-421-20, Mitutoyo, Tokyo, Japan). The maximum accepted specimen size was 2.000 ± 0.020 mm in width and height and 25.000 ± 0.025 mm in length. All procedures were carried out in an air-conditioned room at 23 ± 0.5°C and 50 ± 2% relative humidity.

Before specimens were subjected to flexural testing, they were immersed in distilled water in an incubator at 37°C for 24 h.

Static three-point flexural test

Flexural strength of each specimen was measured using a three-point bending technique with a 20-mm span and a crosshead speed of 0.5 mm/min (Model 5565, Instron, Norwood, MA), as outlined in ISO 9917-2 (1996) (Figure 2). After the specimen was mounted on a test jig, an external force of maximum 5 kgf (49N) was applied to its mid-section until fracture occurred.

Flexural properties were automatically calculated using a bundled software (Series IX, Instron). Flexural strength, σ, was calculated using the following formula:

$$\sigma = (3PL)/(2bd^2)$$

where P is the maximum load at fracture point, L is the distance between supports, b is specimen width and d is specimen height.

Flexural modulus, E, was calculated as follows:

$$E = (P_1L^3)/(4bd^3\delta)$$

where E is the flexural modulus, P_1 is the load at anintersection point within the elastic region of stress-strain curve, l is the distance between supports, b is specimen width, d is specimen height and δ is specimen deformation at P_1.

Fracture energy was given in units of stress times the square root of crack length. Maximum displacement value of each specimen was also measured.

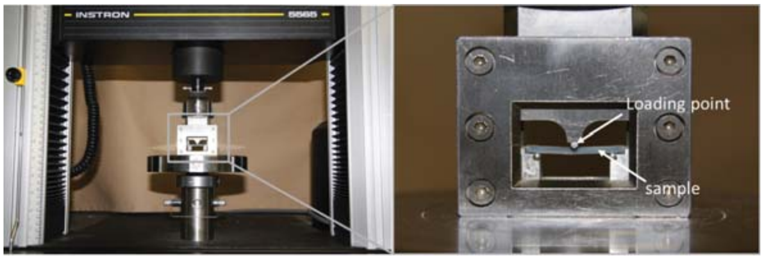

Figure 2. Static three-point flexural test set-up. Resin composite specimen was mounted on test jig.

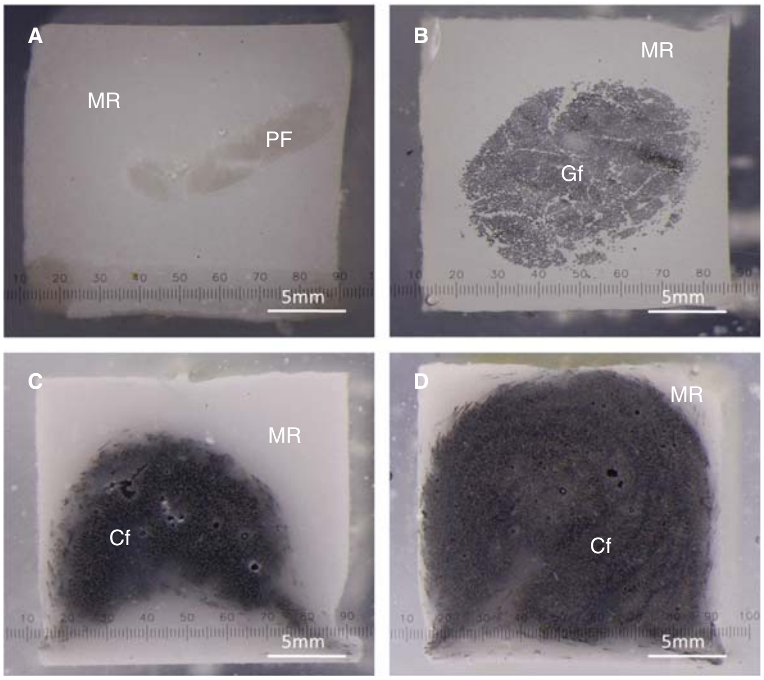

Figure 3. Microscopic images of the cross-sections of each group of resin composites filled with: (A) Polyethylene fiber (Pf) in matrix resin (MR); (B) Glass fiber (Gf); (C) T300B-3K-50B carbon fiber (Cf); and (D) T700SC-12K-50C carbon fiber.

Among the seven groups of specimens, data were statistically compared using one-way analysis of variance (ANOVA) and Tukey's test, with a 5% limit of error ($p < 0.05$) in IBM SPSS Statistics (version 19).

Results

Fiber distribution and localization

Figure 3 shows the microscopic images of the cross-sections of four groups of resin composites filled with fibers. Although fibers were distributed in the resin matrix, each group showed a different degree of fiber localization. Fiber distributions were also different because of differences in their physical form. Polyethylene fiber was in a woven form; glass fiber was in a clod form; and carbon fibers were in a bundled or tuft form (Figure 1).

Flexural strength

Table II shows the mean flexural strengths obtained by the seven groups of specimens in this study. For Construct resin, flexural strength value remained almost the same even when reinforced with polyethylene fiber. In the case of Estenia C&B EG resin, the glass fiber significantly increased the flexural strength ($p < 0.05$). For carbon fiber groups, flexural strength depended on the number of carbon filaments per bundle, with T700SC-12K-50C exhibiting the highest value (464.23 ± 70.49 MPa) among all the groups ($p < 0.05$).

Flexural modulus

Table III shows the mean flexural modulus values obtained by the seven groups of specimens in this study, which exhibited almost the same trend as flexural strength. Addition of polyethylene fiber did not exert a significant effect on the flexural modulus of Construct resin. In contrast, addition of glass fiber and carbon fibers significantly increased flexural modulus ($p < 0.05$).

Fracture energy

Table IV shows the mean fracture energy values obtained by the seven groups of specimens in this study, which exhibited almost the same trend as flexural strength. Interestingly, although Estenia C&B EG resin showed the lowest flexural modulus

Table II. Flexural strength (MPa) of each material.

Product	Mean (SD)
Construct resin*	107.56 (5.62)^{abc}
Construct resin + Construct	97.37 (3.39)^{bc}
Estenia C&B EG flow*	80.77 (3.44)^{c}
Estenia C&B EG flow + EG fiber	300.29 (34.48)^{de}
Clearfil DC core automix	127.87 (11.19)^{abe}
Cleafil DC core automix + T300B-3K-50B	159.35 (15.40)^{de}
Cleafil DC core automix + T700SC-12K-50C	464.23 (70.49)^{d}

Mean values with the same letter (a,b,c,d,e) are not significantly different by Tukey test ($p > 0.05$). *The value of displacement of 3 mm at the test. $n = 10$.

Table III. Flexural modulus (GPa) of each material.

Product	Mean (SD)
Construct resin*	5.75 (0.42)^{ab}
Construct resin + Construct	4.89 (0.60)^{b}
Estenia C&B EG flow*	1.92 (0.26)^{b}
Estenia C&B EG flow + EG fiber	5.91 (1.31)^{ab}
Clearfil DC core automix	9.67 (1.25)^{ac}
Cleafil DC core automix + T300B-3K-50B	11.35 (1.01)^{ac}
Cleafil DC core automix + T700SC-12K-50C	18.50 (1.43)^{c}

Mean values with the same letter (*a*,*b*,*c*) are not significantly different by Tukey test ($p > 0.05$). *The value of displacement of 3 mm at the test. $n = 10$.

Table V. Displacement (mm) of each material.

Product	Mean (SD)
Construct resin	3.00*
Construct resin + Construct	1.13 (0.15)^{a}
Estenia C&B EG flow	3.00*
Estenia C&B EG flow + EG fiber	2.24 (0.28)^{a}
Clearfil DC core automix	0.62 (0.08)^{b}
Cleafil DC core automix + T300B-3K-50B	0.66 (0.07)^{bc}
Cleafil DC core automix + T700SC-12K-50C	1.07 (0.17)^{ac}

Mean values with the same letter (*a*,*b*,*c*) are not significantly different by Tukey test ($p > 0.05$). *Construct resin and Estenia C&B EG flow did not fracture at the test. $n = 10$.

(1.92 ± 0.26 GPa, Table III), its fracture energy (39.16 ± 3.15 mJ) was higher than those of DC Core Automix (9.42 ± 1.98 mJ) and Construct (16.13 ± 3.40 mJ) resins.

Displacement

Table V shows the maximum values of displacement measured for the seven groups of specimens in this study. Construct and Estenia C&B EG Flow resins did not fracture during the three-point flexural test. Reinforcement with glass fiber showed 2.24 ± 0.28 mm of displacement. DC Core Automix showed the lowest displacement value of 0.62 ± 0.08 mm ($p < 0.05$), but addition of carbon fibers to DC Core Automix resin increased the displacement value.

Discussion

Resin composite restorations are routinely subjected to occlusal loading in the oral cavity and fibers composed of different kinds of raw materials and of varied forms have been used to increase their fracture resistance. Fibers can be made of polyethylene, aramid, glass or carbon and they can be in chopped, longitudinal or woven form [22]. In this study, the focus was on whether the longitudinal form of glass and carbon fibers and the woven form of polyethylene fibers could improve the mechanical properties of resin composites.

Table IV. Fracture energy (mJ) of each material.

Product	Mean (SD)
Construct resin*	16.13 (3.40)^{ac}
Construct resin + Construct	16.89 (2.53)^{ac}
Estenia C&B EG flow*	39.16 (3.15)^{ab}
Estenia C&B EG flow + EG fiber	82.37 (12.34)^{b}
Clearfil DC core automix	9.42 (1.98)^{c}
Cleafil DC core automix + T300B-3K-50B	13.77 (2.60)^{ac}
Cleafil DC core automix + T700SC-12K-50C	78.75 (23.49)^{b}

Mean values with the same letter (*a*,*b*,*c*) are not significantly different by Tukey test ($p > 0.05$). *The value of displacement of 3 mm at the test. $n = 10$.

Occlusal force applies at a few contact points on the teeth or prostheses without bolus and masticatory pressure could be concentrated at a single point with the bolus between the teeth or prostheses. The fracture energy was reported to be especially focused on the weakness point in fixed partial dentures with FEM analysis [23] and the concentration of stresses could be related to chipping of outer in prosthetic structure or fracture of the prosthetic devices ultimately. In the present study, a three-point bending test was used to simulate the mechanical stress during mastication in the oral cavity and evaluate the fracture resistance of restorative materials used to build the prosthetic devices. Although laboratory flexural properties under static loading may not reflect intra-oral conditions, these properties are nevertheless helpful in comparing materials under controlled situations and may be a useful predictor of clinical performance [24,25].

Polyethylene fibers have been reported to enhance the flexural properties of polymethyl methacrylate resin [18]. Moreover, unlike carbon fibers, polyethylene fibers do not have a dark appearance. Therefore, polyethylene fibers seemed to be apt and useful for increasing the fracture resistance of dental resin composites against mechanical stress. In the present study, however, polyethylene fibers in woven form did not increase the flexural properties of resin composites, except for improving the displacement (Tables II–V). Discrepancy between this study and the previous studies stemmed from a difference in the degree of fiber distribution in the resin matrix. Fiber distribution was low in the present study (Figure 3), preventing the polyethylene fibers from efficiently exerting their effect of reinforcement against stress. Nonetheless, there was a significant difference in the maximum value of displacement with and without polyethylene fibers ($p < 0.05$). Low displacement against mechanical stress in the oral cavity is good for abutment teeth and oral implants.

Glass fibers are already clinically used to reinforce methacrylate-based denture base resins [26] and frameworks of fixed partial dentures and implant prostheses [10,17]. The clinical success of glass fibers stems not only from their reinforcement effect, but also, by their biocompatibility, good esthetic attributes [19,20] and easy manipulation during the fabrication of prosthetic devices [6]. The reinforcing capability of glass fibers also partially relies on the adhesion between the glass fiber and matrix resin, which can be acquired and enhanced by silane coupling agents [18,20]. In the present study, Estenia C&B EG Fiber supplied by the manufacturer was composed of resin-pre-impregnated, silanized glass fibers. Therefore, the glass fiber significantly improved all the flexural properties of Estenia C&B EG resin composite (Tables II–V).

Several studies have reported on the favorable effects of carbon fibers on the transverse tensile strength and bending modulus of elasticity of resin composites [27]. However, to date, carbon fibers are not popular in the dental field because of their unpleasant color [6]. This esthetic challenge can be overcome by masking with an opaque resin layer, which is conventionally applied on metal frameworks of dental prostheses. In the present study, the carbon fibers improved all the investigated flexural properties (Tables II–IV), although it must be highlighted that their degrees of fiber distribution in the resin matrix were higher than those of polyethylene and glass fibers (Figure 3). Moreover, T700SC-12K-50C with a higher number of 12000 carbon filaments yielded significantly increased flexural strength and fracture energy when compared with T300B-3K-50B ($p < 0.05$). It was highly probable that the thin and soft filaments helped to distribute stress in the resin matrix. A more detailed evaluation could be carried out if information on the surface treatment of carbon fibers were available from the manufacturer.

Mechanical stresses in the oral cavity are multidirectional and complex, which means that fibers in bi-directional or multi-directional arrangement should provide optimal reinforcement [3]. It was initially thought that the woven fiber would provide better reinforcement than the longitudinal fiber, but the results of this study showed otherwise. Degree of fiber distribution and fiber adhesion to the matrix resin also influenced the reinforcement effect. Besides, the influence of fiber orientation on mechanical properties remained unclear.

In conclusion, fibers improved the flexural properties of resin composites, but the effect of reinforcement depended on the fiber type. Carbon fibers in longitudinal form significantly increased the fracture resistance of resin composites.

Acknowledgments

The study was self-funded by the authors and their institution.

***Declaration of interest*:** The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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