Original paper

Dental Materials Journal 18(2) : 167−175, 1999

Temperature-dependence of the Mechanical Properties of FRP Orthodontic Wire

Tohru IMAI, Shuichi YAMAGATA, Fumio WATARI[1], Masahiro KOBAYASHI[2], Kazunori NAGAYAMA, Hiroshi TOYOIZUMI, Masaru UGA and Shinji NAKAMURA

Department of Orthodontics and [1]Department of Dental Materials and Engineering, School of Dentistry, Hokkaido University,
Kita 13, Nishi 7, Kita-ku, Sapporo 060-8586, Japan
[2]Department of Industrial Chemistry, Chiba Institute of Technology,
Tsudanuma 2-17-1, Narashino 275-0016, Japan

Received January 18, 1999/Accepted March 17, 1999

The temperature-dependence of the mechanical properties of a new esthetic orthodontic wire with fiber-reinforced plastic (FRP) structure was investigated. The new FRP wire, fabricated by a hot drawing method, is 0.5 mm in diameter and has a multiple fiber structure composed of biocompatible CaO-P_2O_5-SiO_2-Al_2O_3 glass fibers of 20 μm in diameter and a polymethyl methacrylate matrix. The flexural load at a deflection of 1 mm and Young's modulus at 24, 37, and 50℃ under wet conditions showed similar fiber fraction dependence to those under dry conditions for a fiber fraction of 40-51%. The flexural load and Young's modulus tended to decrease slightly with increases in temperature. This tendency was larger for the lower fiber fraction. However, the difference in flexural load for a temperature difference of between 24℃ and 50℃ was at most 10 gf. This is negligibly small, and a constant orthodontic force regarding temperature change would be advantageous from a clinical point of view.

Key words : Orthodontic wire, Fiber-reinforced plastics (FRP), Temperature dependence

INTRODUCTION

Orthodontic treatment using a multibracket appliance is the most precise method for controlling tooth movement and is indispensable in clinical practice. A multibracket appliance is composed of orthodontic wires and brackets. In this unit, the elastic recovery of deformed archwire is the source of the orthodontic force necessary for tooth movement. Brackets, which need a ligature of orthodontic wire, are adhered to either the buccal or lingual surface of each tooth.

Recently, orthodontic treatment has become more common in adult patients, and the demand for improvement in the esthetic quality of multibracket appliances has been increasing. Up to now, improvement in esthetic quality has been restricted to the brackets. Recently, methods have also been developed to improve the esthetic quality of the orthodontic wire[1-6]. One method is to coat Teflon (polytetrafluoroethylene) or epoxy resin with a dental color on the surface of the metal wire[1]. The other is to fabricate a transparent composite wire comprising a structure of fiber-reinforced plastics (FRP). The only commercialized product of the latter type is orthodontic archwire (Optiflex®, Ormco Company, Glendora, US). Its orthodontic force, however,

is too light for practical use[1]. We have developed a new esthetic FRP wire with a multiple fiber structure that is different from the single fiber structure of Optiflex®. The new esthetic FRP wire is composed of biocompatible CaO-P_2O_5-SiO_2-Al_2O_3 (CPSA) glass fibers[7,8] and a polymethyl methacrylate (PMMA) matrix with a molecular weight of about 100,000. The FRP wires are fabricated by a hot drawing method because it is easy to control the properties using a polymer with a constant degree of polymerization. The structure of the FRP wire is shown in Fig. 1. Long, straight glass fibers are oriented unidirectionally to the longitudinal direction and are distributed uniformly inside a PMMA matrix in the vertical cross section. Fig. 2 shows the dental model in which FRP wires are attached to transparent ceramic brackets. This multibracket appliance using the FRP wire has excellent esthetic quality.

FRP wire has mechanical properties comparable to those of metal wire under dry conditions[3-6]. It was found that the mechanical properties of FRP wire deteriorate when the wire is immersed in water but flexural load at a deflection of 1 mm is maintained at 87% of the level of that under dry conditions after 30 days of water immersion at 37℃[9]. Since intraoral temperature changes during eating or drinking, it is

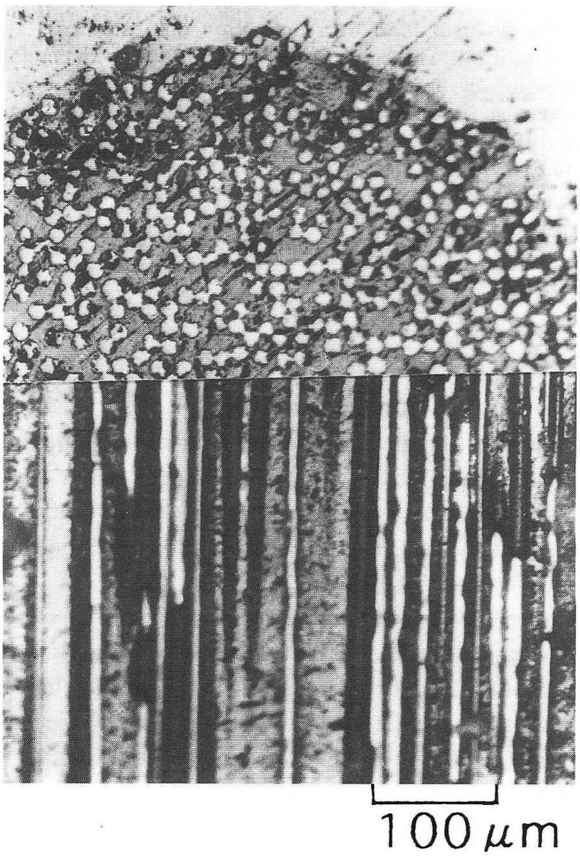

Fig. 1 Structure of FRP wire in vertical (upper) and longitudinal cross sections (lower).

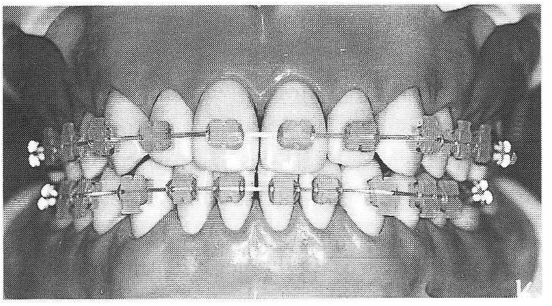

Fig. 2 External appearance of FRP esthetic orthodontic wire attached to polymer brackets on the dental model.

Table 1 Size and glass fiber volume fraction of FRP wires

Glass fiber volume fraction (%)	Glass fiber diameter (μm)	Wire diameter (mm)
21.1	20±2	0.52
32.6	〃	0.52
37.7	〃	0.52-0.53
38.7	〃	0.52-0.53
40.1	〃	0.53
41.7	〃	0.51-0.53
45.4	〃	0.52
47.5	〃	0.53
47.7	〃	0.52
48.2	〃	0.51
50.5	〃	0.52
51.0	〃	0.53
60.4	〃	0.52

necessary to determine the temperature dependence of the wire under wet conditions. In this study, the mechanical properties of the FRP wire immersed in water were investigated at three different temperatures: 24, 37, 50℃.

MATERIALS AND METHOD

FRP wires were fabricated by the hot drawing of glass fibers and PMMA. After long, straight glass fibers were made from the CPSA glass pellets, the surfaces of the fibers were treated with a silane-coupling agent to improve bonding strength at the interface between the fibers and the polymer matrix. The fibers were then coagulated with PMMA in an acetone solution, and the resulting glass fiber-PMMA complex was formed into FRP wire of 0.5 mm in diameter by drawing at a high temperature (typically 250℃) through a glass die with a capillary to reduce the wire diameter. Volume fraction of CPSA glass fibers were determined from the ratio of the residual weight after firing (JIS K 7052).

Table 1 shows the FRP wires used for mechanical testing under dry conditions. The CPSA glass fiber diameter was about 20μm, and the external diameter of FRP wire was about 0.5 mm. The fiber fraction varied within the range of 21.1-60.4%. Mechanical testing under dry conditions was carried out for these FRP wires[6]. Of the wires listed in Table 1, those with fiber fractions of 40.1, 41.7, 48.2, and 51.0% were used as specimens for the mechanical testing at different temperatures (24, 37, and 50℃) under wet conditions.

To investigate the temperature dependence of the mechanical properties of the FRP wire under wet conditions, 3-point flexural tests with a gauge length of 14 mm and cross-head speed of 1.0 mm/min were performed in a temperature variable water bath (Fig. 3). Before testing, all specimens were immersed in water for 10 days at the same temperature as the testing temperature. Under dry conditions, three specimens were tested at 23℃ in 50% moisture, and five specimens were tested under wet conditions at each temperature. The flexural load at a deflection of 1 mm was measured from the load-deflection curve and modulus of longitudinal elasticity (Young's modulus) E was deduced using the relation $E=4Pl^3/(3\pi \delta d^3)$ where P is flexural load, δ is deflection, l is gauge length, d is wire diameter. These data were statistically analyzed by Student's t-test.

RESULTS

Figs. 4 and 5 show the dependence of flexural load at a deflection of 1 mm and Young's modulus on fiber fraction, respectively. The data are represented by open circles for dry conditions which were previously obtained[6] and by filled marks for wet conditions obtained in this study. In the scale of these graphs, the values under wet conditions are so close that they appear to almost overlap. The straight line was drawn using the least squares method for the data of the fiber fraction of 21.1-60.4% under dry conditions. The point at the fiber fraction of 0 % is the value of PMMA

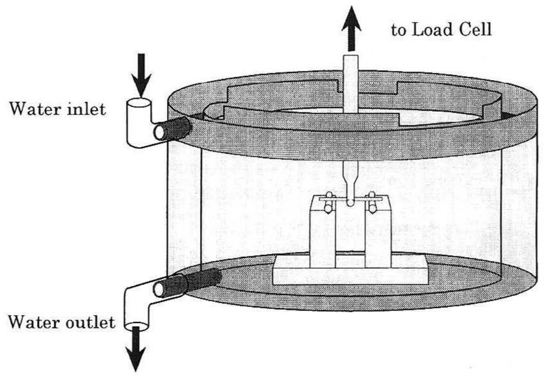

Fig. 3 Schematic diagram of the temperature variable water bath for the 3-pointflexural test.

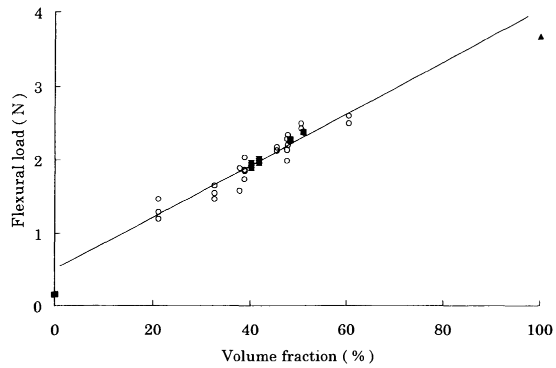

Fig. 4 Dependence of flexural load at a deflection of 1 mm on fiber fraction. The open circles are values obtained under dry conditions and the filled marks are values obtained under wet conditions.

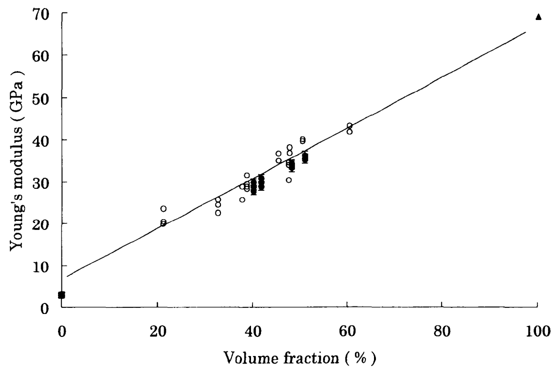

Fig. 5 Dependence of Young's modulus on fiber fraction. The open circles are values obtained under dry conditions and the filled marks are values obtained under wet conditions.

and that at the fiber fraction of 100% is the value of CPSA glass. The relation showed a linear increase and approximately satisfied the rule of mixture. When seen more precisely, the values of flexural load at a deflection of 1 mm were slightly over the line connecting the points of PMMA (0 %) and CPSA glass (100%). The line for Young's modulus was nearly on the connecting line.

The dependence on temperature and on fiber fraction under wet conditions is shown as a three-dimensional bar graph for flexural load at a deflection of 1 mm in Fig. 6 and for Young's modulus in Fig. 7. The enlarged scale used in the graphs enables the differences between data groups to be seen easily. The results of the Student's t-test are also shown for the group combination that demonstrated a significant difference ($^{*}p<0.05$, $^{**}p<0.005$, $^{***}p<0.001$). From both figures, it is

clear that flexural load and Young's modulus became larger with the increase in the fiber fraction. The standard deviations were sufficiently small under all the experimental conditions, 0.026-0.034 N for flexural load and 0.78-0.98 GPa for Young's modulus. There were significant differences in both flexural load and Young's modulus at 24℃ and 50℃ in the case of wires with a fiber fraction of 40.1% and 41.7%. The difference in temperature dependence between the groups was small. However, there was a general tendency for the flexural load and Young's modulus to become small with the increase in temperature. The tendency was larger for lower fiber fractions (40.1% and 41.7%).

DISCUSSION

A previous study[9] showed that most of the decrease in flexural load at a deflection of 1 mm and in Young's modulus due to stress relaxation occurs within 15 min. of water immersion. The dependence of the mechanical properties on the fiber fraction under wet conditions was similar to that under dry conditions, as shown in Figs. 4 and 5. The effect of temperature change was low. The decrease in flexural load at a deflection of 1 mm and in Young's modulus with temperature was greater in FRP wires with a lower fiber fraction (i.e., a larger fraction of matrix PMMA resin), although the difference was small (Figs. 6 and 7).

One reason for the greater temperature dependence for the higher resin fraction might be due to water absorption. The water absorption in PMMA resin is known to be larger in higher temperatures and this often causes the deterioration of mechanical properties. In composite resin the water absorption lowers the bonding strength at the interface between ceramic fillers and the resin matrix which is strengthened with the aid of a silane coupling agent. A similar effect might have also occurred in the present case. However, this would not be large as far as the Young's modulus and flexural load at a deflection of 1 mm in 14 mm gauge length for the wire diameter of

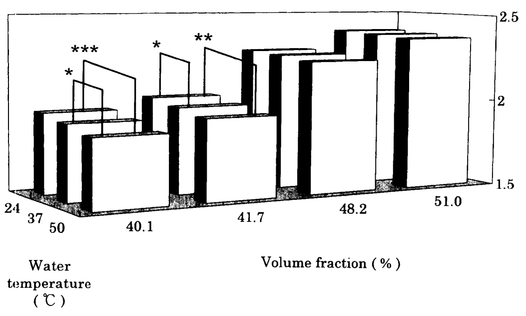

Fig. 6 Flexural load for different fiber fractions and testing temperatures under wet conditions. Significant intergroup differences are indicated by *$p<0.05$, **$p<0.005$, and ***$p<0.001$.

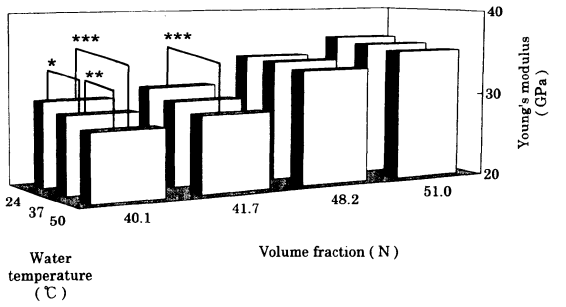

Fig. 7 Young's modulus for different fiber fractions and testing temperatures under wet conditions. Significant intergroup differences are indicated by $^{*}p<0.05$, $^{**}p<0.005$, and $^{***}p<0.001$.

0.5 mm. Since these properties are related to the phenomenon at a small strain of less than 1 %, the discrepancy at the interface for different materials is still small, therefore shear sliding, debonding or partial fracture are not serious at this stage. In such a strain range the effect of silane coupling is not dominant. The properties are determined simply by the average of two different components, that is, by the rule of mixture. In a larger deflection range of around 2 mm the difference in mechanical properties is no more negligible. Water absorption and the treatment with silane coupling agent play key roles in mechanical behavior. Water absorption might thus play a limited role in the decrease of flexural load and Young's modulus for the deflection range in this study.

Another reason may be the difference in softening tendency when the materials are heated. The softening temperature of PMMA is much lower than that of CPSA glass. The influence of temperature change is larger in materials with lower softening points. Therefore, as the volume fraction of PMMA is higher, the composite tends to be softened more with an increase in temperature, as was the case in this study.

FRP wires showed the mechanical properties of a relatively small load (50-400 gf) and good elastic recovery. Since this is similar to the so-called work-hardening type superelastic Ni-Ti, the use of FRP wires would be the most suitable for the initial stage of orthodontic treatment rather than at the later stage which needs sufficient torque and where Co-Cr wire is now used. Therefore, the first clinical application would be the replacement of Ni-Ti wire in the initial stage. When Ni-Ti and FRP wires are compared, the temperature dependence of the mechanical properties is large in Ni-Ti, whereas it is small in FRP wires. The small change in mechanical properties in temperature changes would be advantageous in clinical practice. In superelastic Ni-Ti wire the orthodontic force changes greatly with changes in temperature[10-13]. This sometimes causes pain or discomfort. This is because Ni-Ti utilizes superelasticity based on the martensitic phase transformation, which is strongly temperature-

dependent. On the other hand, the FRP wires used in this study have properties based on the rule of composite[4], that is, in accordance with the volume fraction of both components. Therefore, there was little change in the properties of the FRP wires in changes in temperature within the range of 24 to 50℃. The significant difference in flexural load revealed by statistical analysis was less than 10 gf. From a clinical view point, this is much smaller than the effective orthodontic force. Thus, changes in intraoral temperature would have little effect on FRP wire.

In the present study, the deflection in flexural tests was set at 1 mm, which is less than in most cases of orthodontic treatment. Further study is therefore needed to elucidate the phenomena that occur under conditions of greater strain.

CONCLUSIONS

The influence of water immersion and the dependence of mechanical properties on temperature of a new esthetic orthodontic wire with an FRP structure was investigated. Flexural load at a deflection of 1 mm and Young's modulus in 3-point flexural tests under wet conditions showed a similar fiber fraction-dependence to those under dry conditions; that is, both values increased with the fiber fraction in accordance with the rule of composite. Flexural load and Young's modulus decreased slightly with increases in temperature. These decreases were greater in FRP wires with a lower fiber fraction. The significant difference in flexural load with changes in temperature within the range of 24℃ to 50℃ is at most 10 gf, which is negligible from a clinical point of view. The insensibility of FRP wire to temperature change is advantageous in clinical practice.

ACKNOWLEDGMENTS

This research was supported by a Grants-in-Aid for Scientific Research (Nos.08672353 and 10357019) from the Ministry of Education, Science and Culture, Japan.

REFERENCES

1) Lim, K. F., Lew, K. K. K. and Toh: Bending stiffness of two aesthetic orthodontic archwires: An in vitro comparative study. *Clin Mater* **16** : 63-71, 1994.
2) Kusy, R.P: A review of contemporary archwires: Their properties and characteristics. *Angle Orthod* **67** : 197-208, 1997.
3) Watari, F., Kobayashi, M., Yamagata, S., Nagayama, K., Imai, T. and Nakamura S.: Structure and properties of the FRP esthetic orthodontic wire, Proc Int Conf on Microstructures and Functions of Materials (ICMFM96), ed. Igata N., Noda: Sci. Univ. Tokyo, 141-144, 1996.
4) Watari, F., Kobayashi, M., Yamagata, S., Nagayama, K., Imai, T. and Nakamura, S.: Properties of the unidimensionally glass fiber reinforced composite wire for an esthetic orthodontic wire, Bioceramics vol.9 (Proc. 9th Int. Symp. on Ceramics in Medicine), ed. Kokubo, T., Oxford: Pergamon/Elsevier, 469-472, 1996.
5) Watari, F., Yamagata, S., Imai, T., Kobayashi, M. and Nakamura, S.: Fabrication of FRP wires for esthetic orthodontic wire and their properties, *J Mater Sci*, to be

published, 1999.

6) Imai, T., Watari, F., Yamagata, S., Kobayashi, M., Nagayama, K. and Nakamura, S.: Mechanical properties and estheticity of FRP orthodontic wire fabricated by hot drawing, *Biomater* **19** : 2195-2200, 1998.

7) Kobayashi, M., Tagai, H., Kuroki, Y., Niwa, S. and Ono, M.: Development and properties of glass fiber composite materials as artificial bone. *Orthopaedic Ceramic Implants* **4** : 79-82, 1984. (in Japanese)

8) Morishita, M., Kobayashi M., Seyama, M., Kondo, S., Kawauchi K., Arai, H., Tagai, H. and Kuroki, Y.: Mechanical properties and biocompatibilities of the new glass-fiber composite materials as artificial bone, *Biomaterials and Clinical Applications* **7** : 275-280, 1987.

9) Imai, T., Watari, F., Yamagata, S., Kobayashi, M., Nagayama, K. and Nakamura, S.: Effects of water immersion on mechanical properties of new esthetic orthodontic wire, *Am J Orthod Dentofac Orthop*, to be published, 1999.

10) Andreasen, G. F., Heilmann, H. and Krell, D.: Stiffness changes in thermodynamic nitinol with increasing temperature, *Angle Orthod* **55** : 120-126, 1985.

11) Yoneyama, T., Doi, H., Hamanaka, H., Okamoto, Y., Mogi, M. and Miura, F.: Superelasticity and thermal behavior of Ni-Ti alloy orthodontic arch wires, *Dent Mater J* **11** : 1-10, 1992.

12) Tonner, R. I. and Waters, N. E.: The characteristics of super-elastic Ni-Ti wires in three point bending. Part I : The effect of temperature, *Eur J Orthod* **16** : 409-419, 1994.

13) Meling, T. and Ødegaard, J.: Short-term temperature changes influence the force exerted by superelastic nickel-titanium archwires activated in orthodontic bending, *Am J Orthod Dentofac Orthop* **114** : 503-509, 1998.