Comparative Investigation on the Effect of Fiber Additives with Different Characteristics on the Mechanical Strength of Heat-cured PMMA Denture Base Resins

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Research Article

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Abstract

Background:

To determine and compare effects on mechanical properties using glass, polypropylene and carbon fibers with 3, 6- and 12-mm lengths, and 0.25, 0.50 and 1.0% concentrations (v/v) as reinforcement of PMMA denture base resins.

Methods:

In order to enhance mechanical properties glass fibers, polypropylene fibers and carbon fibers with 3, 6 and 12mm lengths were added to the resin in different fiber volume to resin volume ratios (0.25, 0.50 and 1.0% v/v). Mechanical properties (flexural strength, modulus of elasticity and ultimate tensile strength) were comparatively investigated using three-way ANOVA tests on the results of three point bending and tensile tests. Morphologies of the fracture surfaces were analyzed using scanning electron microscopy.

Results:

All three fibers exhibited reinforcement in flexural strength ($P < 0.05$) regardless of their length ($P > 0.05$) but concentration had significant effect. Denture base resin reinforced by glass fibers or carbon fibers exhibited increase in modulus of elasticity, using polypropylene fibers for reinforcement decreased the modulus of elasticity. Carbon fiber reinforced resin at 0.25% concentrations showed greater ultimate tensile values.

Conclusions:

Reinforcement with glass fibers, polypropylene fibers and carbon fibers resulted with enhanced mechanical properties. Fiber type and fiber concentration had significant effect on both flexural and tensile properties, while fiber length did not exhibit significance on mechanical properties.

Introduction

Since early 1940's, PMMA became the most widely preferred and used denture base material by prosthodontists and other dentists[1, 2]. Features such as aesthetic appearance, easy processing and low cost have made PMMA a widely used base material in prosthetic dentistry[3–5]. Besides these, PMMA is biocompatible, safe, dimensionally stable, non-taste and odor, non-irritant, non-toxic, stable in the oral environment, insoluble with saliva and color stable[6]. Despite these excellent properties PMMA has unfavorable weakness in some mechanical and physical properties such as impact resistance, flexural strength and fatigue fracture[7, 8]. 63–68% of the dentures become useless because of the fracture as a result of fatigue fracture due to chewing forces while in mouth or breaking due to accidental fall on hard surfaces while out of mouth[9, 10]. In order to avoid fractures, strategies like enhancing PMMA denture base by metal wire were used but poor adhesion between the metal wire and the PMMA matrix was the main problem with this strategy[8, 10–13]. Another application for this purpose was forming a graft copolymer of PMMA and butadiene styrene but it was found to be weaker than PMMA because of the low bending strength compared to conventional acrylic resin despite its high impact resistance[14, 15].

Carbon fibers, aramid fibers, high molecular weight polyethylene fibers and similar fibers were used as denture base enhancing materials and it was reported that these fibers increased the bending and impact strength of the denture base resin[5, 8, 16–18]. Due to their biocompatibility, aesthetic compatibility and mechanical properties, nylon fiber, polyethylene fibers, polyamide fibers and especially glass fibers were used in several studies[16, 17, 19, 20]. Enhancing effect of glass fibers on bending properties and fatigue resistance of PMMA denture base resin was previously reported[8, 16, 19, 21, 22]. Polypropylene is suitable material for PMMA base resin reinforcement because of its properties such as high-level resilience, elasticity and tensile strength, durable in acid and similar medium, low density (0.91 g/cm^3) and low cost[23, 24]. Carbon fiber was shown to increase the bending strength of the PMMA denture base resin[25].

In this study it was aimed to comparatively investigate the effect of fiber reinforcement using fibers with different characteristics, namely different materials [glass, polypropylene (PP), and carbon], three fiber lengths (3, 6 and 12 mm), and three different concentrations (0.25, 0.50 and 1.0% v/v), on mechanical properties of PMMA denture base resin. As described above, various fibers were used in order to enhance the mechanical properties of the PMMA denture base resin, but none of these studies reported a comparative investigation about effects of fiber materials, fiber lengths and fiber concentrations on mechanical properties. In order to eliminate the effect of differences in densities of each fiber material, volumetric ratios for fiber reinforcement was used instead of weight ratios using appropriate calculations.

Materials And Methods

Heat-cured PMMA denture base resin was composed of two components, powder and liquid (Akrodent, Koca Kimya ve Dental Ltd. Şti., Ankara, Turkey). PP fibers (Polyfibers, İstanbul, Turkey), glass fibers (Dost Kimya, İstanbul, Turkey) and carbon fibers (Dost Kimya, İstanbul, Turkey) were used as received. No further treatment was performed on the fibers to maintain similar conditions for each fiber type. The ideal powder-liquid mixture ratio was used as 23.4g powder to 10 ml liquid and complete wetting was observed. A mold was produced from chromium for sample production. Control and fiber reinforced groups were designed in 65x10x3 mm dimensions for three point bending test, and tensile test samples were designed to match dimensions described in ASTM D638-14 standard. A representative image of the test specimens after three-point bending test and tensile test was shown in Fig. 1. Curing reaction of the PMMA denture base resin was carried out within the mold.

There were three fiber reinforced groups; glass fiber, PP fiber and carbon fiber and each group was produced using 3, 6 and 12mm fibers in 0.25, 0.50 and 1.0% v/v concentrations for each fiber type and length. A total of 352 samples in 22 groups and n = 8 samples for each group including control was formed for both three point bending tests (176 samples) and tensile tests (176 samples). PMMA powder-liquid mixtures were placed in the mold and reaction was carried out in a fully automatic polymerization device (MD-135, Meta Dental, Ankara, Turkey). Reactions were implemented in this equipment by heating from room temperature (25°C) to 90°C and kept the temperature constant for 20 minutes. At the end of the reaction period mold was taken out and then left to cool down to room temperature followed by the removal of the samples from the mold.

Three point bending and tensile tests were performed using universal testing machine (Shimadzu AGS-X, Japan). Three point bending tests were performed at a compression rate of 10 mm/min on the samples placed between the shoulders having a gap of 45 mm. Tensile tests were performed using the standard apparatus at 5 mm/min drawing rate. All tests were carried out at room temperature and mechanical properties of the samples were investigated.

Morphologies of the fracture surfaces that were obtained from three point bending tests were investigated through the SEM images taken from these surfaces. Fractured test specimens were cut to reduce height to 5 mm long for SEM analyses. Test specimens were positioned on the sample tray as the fracture surfaces facing up. SEM specimens were coated with Au under vacuum atmosphere in coating instrument (Quorum K150RS, UK). SEM images were collected by SEM equipment (Tescan Mira3 XMU, Czechia) with an accelerating voltage of 10 kV.

Flexural strength from three-point bending test, modulus of elasticity and ultimate stress from tensile test were analyzed using the three-way ANOVA test and level of significance was set to $P < 0.05$. Bonferroni corrections were performed for multiple comparisons. All the statistical analyses were carried out using statistics software SPSS 20 (IBM, Chicago, IL, USA).

Results

Mechanical Tests

Test results for between subject effects obtained by three-way ANOVA analysis of three point bending and tensile test results are summarized on Table 1. Mean and standard deviations, and significance of the tested variables obtained by pairwise comparisons are presented in Table 2 for three point bending test results, and Table 3 for tensile test results. These results revealed that using any of three fiber material (GF, PPF and CF) at any volume ratio (concentration) exhibited statistically significant increase on flexural strength of the PMMA denture base resins ($P < 0.001$). However, using these fibers in increasing concentrations resulted with a decrease in flexural strength ($P < 0.05$). Pairwise comparisons did not show significant difference for the fiber length parameter on flexural strength regardless of fiber material or concentration ($P = 0.697$). Although concentration did not result with a significant change for PPF reinforcement, use of GF at 1.0% ratio resulted with a decrease in flexural strength regardless of GF fiber length ($P < 0.05$). The greatest value of flexural strength was observed as 90.72 ± 8.95 MPa with 12 mm PPF reinforced PMMA denture base resin using 0.25% fiber to matrix ratio (Fig. 2A).

Table 1
Test results for between subject effects obtained by three-way ANOVA analysis

Variable	Comparison	Sum of Squares	df	Mean Square	F	P
Flexural strength by three point bending test	Material	1618.921	2	809.461	8.436	.000*
	Concentration	1202.378	2	601.189	6.265	.002*
	Length	69.409	2	34.705	.362	.697
	Material × Concentration	664.790	2	332.395	3.464	.034*
	Material × Length	336.474	4	84.118	.877	.479
	Concentration × Length	71.625	4	17.906	.187	.945
	Material × Concentration × Length	481.150	4	120.288	1.254	.291
Modulus of elasticity by tensile test	Material	1092765.548	2	546382.774	10.099	.000*
	Concentration	311276.321	2	155638.160	2.877	.059+
	Length	39338.882	2	19669.441	.364	.696
	Material × Concentration	558926.378	2	279463.189	5.165	.007*
	Material × Length	432107.294	4	108026.824	1.997	.098+
	Concentration × Length	904552.711	4	226138.178	4.180	.003*
	Material × Concentration × Length	630841.921	4	157710.480	2.915	.023*
Ultimate tensile stress by tensile test	Material	882.859	2	441.429	7.448	.001*
	Concentration	12.948	2	6.474	.109	.897
	Length	426.202	2	213.101	3.595	.030*
	Material × Concentration	182.125	2	91.062	1.536	.218
	Material × Length	136.724	4	34.181	.577	.680
	Concentration × Length	158.829	4	39.707	.670	.614
	Material × Concentration × Length	228.682	4	57.171	.965	.429

Variable: *Dependent variable;* Material: *Fiber material;* Concentration: *Fiber volume/resin volume;* Length: *Fiber length*

*: *Statistically significant difference;* +: *Statistically comparable difference*

Table 2
Mean, standard deviations, and significance by pairwise comparisons for three point bending test

	Length	Concentration	Control	Glass Fiber	PP Fiber	Carbon Fiber	Total
	0mm	0%	61.39 ± 7.95				61.4 ± 7.95
Flexural strength (MPa)		Total	61.39 ± 7.95				61.4 ± 7.95$^{(x)}$
	3mm	0%					
		0.25%		83.13 ± 4.98$^{(m,a,x)}$	85.66 ± 5.27$^{(m,a,x)}$	88.86 ± 9.03$^{(m,x)}$	85.88 ± 6.82$^{(a,x)}$
		0.50%		80.08 ± 10.67$^{(m,a,x)}$	83.87 ± 8.05$^{(m,a,x)}$		81.98 ± 9.34$^{(ab,x)}$
		1.0%		66.86 ± 10.42$^{(m,b,x)}$	87.14 ± 8.66$^{(n,a,x)}$		77 ± 13.98$^{(b,x)}$
		Total		76.69 ± 11.28$^{(m,x)}$	85.55 ± 7.27$^{(n,x)}$	88.86 ± 9.03$^{(n,x)}$	82.23 ± 10.5$^{(y)}$
	6mm	0%					
		0.25%		86.2 ± 13.15$^{(m,a,x)}$	84.75 ± 11.17$^{(m,a,x)}$	87.55 ± 12.17$^{(m,x)}$	86.17 ± 11.71$^{(a,x)}$
		0.50%		80.8 ± 12.5$^{(m,ab,x)}$	85.43 ± 9.84$^{(n,a,x)}$		83.12 ± 11.13$^{(ab,x)}$
		1.0%		71.79 ± 11.15$^{(m,b,x)}$	82.64 ± 8.34$^{(n,a,x)}$		77.22 ± 11.04$^{(b,x)}$
		Total		79.6 ± 13.22$^{(m,x)}$	84.27 ± 9.49$^{(m,x)}$	87.55 ± 12.17$^{(m,x)}$	82.74 ± 11.76$^{(y)}$
	12mm	0%					
		0.25%		81.83 ± 9.7$^{(m,a,x)}$	90.72 ± 8.95$^{(m,a,x)}$	81.77 ± 10.63$^{(m,x)}$	84.77 ± 10.29$^{(a,x)}$
		0.50%		84.88 ± 10.64$^{(m,a,x)}$	88.48 ± 7.39$^{(m,a,x)}$		86.68 ± 9.04$^{(a,x)}$
		1.0%		78.17 ± 12.6$^{(m,a,x)}$	85.33 ± 6.65$^{(m,a,x)}$		81.75 ± 10.41$^{(a,x)}$
		Total		81.63 ± 10.92$^{(m,x)}$	88.18 ± 7.72$^{(m,x)}$	81.77 ± 10.63$^{(m,x)}$	84.46 ± 9.99$^{(y)}$
	Total	0%	61.39 ± 7.95				61.4 ± 7.95$^{(a)}$

Three way variance analysis was used, Comparisons; (xyz): for fiber length (abc): for concentration, (mno): for fiber material, values with different superscript letters indicate significant difference

	Length	Concentration	Control	Glass Fiber	PP Fiber	Carbon Fiber	Total
		0.25%		83.72 ± 9.62$^{(m,a)}$	87.04 ± 8.83$^{(m,a)}$	86.06 ± 10.69$^{(m)}$	85.61 ± 9.71$^{(b)}$
		0.50%		81.93 ± 11.02$^{(m,a)}$	85.92 ± 8.34$^{(m,a)}$		83.93 ± 9.88$^{(bc)}$
		1.0%		72.28 ± 11.9$^{(m,b)}$	85.03 ± 7.81$^{(n,a)}$		78.66 ± 11.86$^{(c)}$
		Total	61.39 ± 7.95$^{(m)}$	79.31 ± 11.86$^{(n)}$	86 ± 8.26$^{(o)}$	86.06 ± 10.69$^{(o)}$	82.15 ± 11.56

Three way variance analysis was used, Comparisons; (xyz): for fiber length (abc): for concentration, (mno): for fiber material, values with different superscript letters indicate significant difference

Table 3
Mean, standard deviations, and significance by pairwise comparisons for tensile test

	Length	Concentration	Control	Glass Fiber	PP Fiber	Carbon Fiber	Total
	0mm	0%	3003.7 ± 194.20				3003.7 ± 194.20
Modulus of Elasticity (MPa)		Total	3003.7 ± 194.20				3003.7 ± 194.20$^{(x)}$
	3mm	0%					
		0.25%		2917.49 ± 152.43$^{(mn,a,x)}$	2841.05 ± 185.44$^{(m,a,x)}$	3172.81 ± 223.64$^{(n,x)}$	2977.11 ± 231.85$^{(a,x)}$
		0.50%		3190.76 ± 133.78$^{(m,a,x)}$	2935.35 ± 219.16$^{(n,a,x)}$		3063.06 ± 219.46$^{(a,x)}$
		1.0%		3191.91 ± 283.36$^{(m,a,xy)}$	2913.34 ± 428.20$^{(n,a,x)}$		3052.63 ± 379.11$^{(a,x)}$
		Total		3100.05 ± 233.12$^{(m,x)}$	2896.58 ± 287.37$^{(n,x)}$	3172.81 ± 223.64$^{(m,x)}$	3023.24 ± 276.50$^{(x)}$
	6mm	0%					
		0.25%		3192.75 ± 248.38$^{(m,a,xy)}$	2921.42 ± 124.62$^{(m,a,x)}$	2976.27 ± 207.74$^{(m,x)}$	3030.14 ± 225.73$^{(a,x)}$
		0.50%		3162.16 ± 149.71$^{(m,a,x)}$	2793.78 ± 143.48$^{(n,a,x)}$		2977.97 ± 237.18$^{(a,x)}$
		1.0%		3210.55 ± 123.06$^{(m,a,x)}$	3359.74 ± 301.09$^{(m,b,y)}$		3285.14 ± 235.18$^{(b,y)}$
		Total		3188.49 ± 174.99$^{(m,x)}$	3024.98 ± 316.04$^{(n,x)}$	2976.27 ± 207.74$^{(mn,x)}$	3088.1 ± 260.81$^{(x)}$
	12mm	0%					
		0.25%		3244.72 ± 107.84$^{(m,a,y)}$	2927.26 ± 163.25$^{(n,a,x)}$	3103.36 ± 272.52$^{(mn,x)}$	3091.78 ± 227.71$^{(a,x)}$
		0.50%		3141.32 ± 114.04$^{(m,ab,x)}$	2913.45 ± 190.84$^{(m,a,x)}$		3027.38 ± 192.12$^{(a,x)}$

Three way variance analysis was used, Comparisons; (xyz): for fiber length (abc): for concentration, (mno): for fiber material, values with different superscript letters indicate significant difference

	Length	Concentration	Control	Glass Fiber	PP Fiber	Carbon Fiber	Total
		1.0%		2927.13 ± 353.65$^{(m,b,y)}$	3074.43 ± 398.93$^{(m,a,x)}$		3000.78 ± 372.05$^{(a,x)}$
		Total		3104.39 ± 252.61$^{(m,x)}$	2971.71 ± 270.50$^{(m,x)}$	3103.36 ± 272.52$^{(m,x)}$	3047.38 ± 266.66$^{(x)}$
	Total	0%	3003.7 ± 194.20				3003.7 ± 194.20$^{(a)}$
		0.25%		3118.32 ± 225.61$^{(m,a)}$	2896.57 ± 157.85$^{(n,a)}$	3084.15 ± 240.56$^{(m)}$	3033.01 ± 230.09$^{(a)}$
		0.50%		3164.75 ± 129.05$^{(m,a)}$	2880.86 ± 189.76$^{(n,a)}$		3022.8 ± 215.28$^{(a)}$
		1.0%		3109.87 ± 290.85$^{(m,a)}$	3115.84 ± 409.12$^{(m,b)}$		3112.85 ± 351.16$^{(a)}$
		Total	3003.7 ± 194.20$^{(mn)}$	3130.98 ± 223.33$^{(m)}$	2964.42 ± 292.62$^{(n)}$	3084.15 ± 240.56$^{(mn)}$	3050.67 ± 264.68
	0mm	0%	56.88 ± 10.18				56.88 ± 10.18
Ultimate Tensile Stress (MPa)		Total	56.88 ± 10.18				56.88 ± 10.18$^{(x)}$
	3mm	0%					
		0.25%		60.67 ± 6.74$^{(m,a,x)}$	59.78 ± 5.04$^{(m,a,x)}$	68.39 ± 7.19$^{(m,,x)}$	62.95 ± 7.27$^{(a,x)}$
		0.50%		60.01 ± 5.61$^{(m,a,x)}$	63.09 ± 7.32$^{(m,a,x)}$		61.55 ± 6.50$^{(a,x)}$
		1.0%		53.91 ± 9.86$^{(m,a,x)}$	64.58 ± 8.40$^{(n,a,x)}$		59.25 ± 10.42$^{(a,x)}$
		Total		58.2 ± 7.92$^{(m,x)}$	62.48 ± 7.05$^{(mn,x)}$	68.39 ± 7.19$^{(n,x)}$	61.49 ± 8.10$^{(x)}$
	6mm	0%					
		0.25%		59.62 ± 6.21$^{(m,a,x)}$	57.68 ± 11.16$^{(m,a,x)}$	62.16 ± 10.63$^{(m,x)}$	59.82 ± 9.36$^{(a,x)}$
		0.50%		53.81 ± 7.63$^{(m,a,x)}$	58.25 ± 5.28$^{(m,a,x)}$		56.03 ± 6.74$^{(a,x)}$

Three way variance analysis was used, Comparisons; (xyz): for fiber length (abc): for concentration, (mno): for fiber material, values with different superscript letters indicate significant difference

Length	Concentration	Control	Glass Fiber	PP Fiber	Carbon Fiber	Total
	1.0%		54.85 ± 6.00$^{(m,a,x)}$	60.04 ± 5.03$^{(m,a,x)}$		57.44 ± 5.98$^{(a,x)}$
	Total		56.09 ± 6.86$^{(m,x)}$	58.66 ± 7.43$^{(m,x)}$	62.16 ± 10.63$^{(m,x)}$	58.06 ± 7.84$^{(x)}$
12mm	0%					
	0.25%		58.2 ± 5.69$^{(m,a,x)}$	59.96 ± 5.83$^{(m,a,x)}$	66.46 ± 10.51$^{(m,x)}$	61.54 ± 8.18$^{(a,x)}$
	0.50%		57.87 ± 6.78$^{(m,a,x)}$	59.19 ± 7.99$^{(m,a,x)}$		58.53 ± 7.19$^{(a,x)}$
	1.0%		61.65 ± 8.70$^{(m,a,x)}$	61.13 ± 6.25$^{(m,a,x)}$		61.39 ± 7.32$^{(a,x)}$
	Total		59.24 ± 7.07$^{(m,x)}$	60.09 ± 6.50$^{(m,x)}$	66.46 ± 10.51$^{(m,x)}$	60.64 ± 7.65$^{(x)}$
Total	0%	56.88 ± 10.18				56.88 ± 10.18$^{(a)}$
	0.25%		59.5 ± 6.04$^{(m,a)}$	59.14 ± 7.56$^{(m,a)}$	65.67 ± 9.53$^{(n)}$	61.44 ± 8.30$^{(a)}$
	0.50%		57.23 ± 6.94$^{(m,a)}$	60.18 ± 6.99$^{(m,a)}$		58.7 ± 7.05$^{(a)}$
	1.0%		56.8 ± 8.72$^{(m,a)}$	61.92 ± 6.71$^{(n,a)}$		59.36 ± 8.12$^{(a)}$
	Total	56.88 ± 10.18$^{(m)}$	57.84 ± 7.31$^{(m)}$	60.41 ± 7.09$^{(m)}$	65.67 ± 9.53$^{(n)}$	59.92 ± 8.06

Three way variance analysis was used, Comparisons; (xyz): for fiber length (abc): for concentration, (mno): for fiber material, values with different superscript letters indicate significant difference

Statistical analyses of the tensile test results revealed that fiber reinforcement significantly affected the modulus of elasticity ($P < 0.001$), but concentration and fiber length did not exhibit significant difference ($P > 0.05$). Although using GF and CF fibers for reinforcement resulted with an increase in modulus of elasticity, using PPF for reinforcement decreased the modulus of elasticity compared to control except for 1.0% concentrations of 6 and 12 mm PPF. The greatest value of modulus of elasticity was observed as 3359.74 ± 301.09 MPa with 6 mm PPF reinforced PMMA denture base resin using 1.0% fiber to matrix ratio (Fig. 2B). Despite the statistical insignificance of fiber length parameter on modulus of elasticity ($P = 0.696$), two way and three-way interactions exhibited significance ($P = 0.003$ and $P = 0.023$ respectively). Reinforcement with CF showed the best ultimate tensile strength regardless of fiber length used ($P < 0.001$). Use of 3 mm PPF at 1.0% concentration for reinforcement exhibited greatest ultimate tensile stress (UTS) value of 64.58 ± 8.40 MPa compared to GF use ($P = 0.006$) (Fig. 2C).

SEM analyses

SEM images were obtained from the fracture surfaces of the specimens used in three-point bending tests. 100X SEM images from the fractured control, GF reinforced denture base resin, PPF reinforced denture base resin and CF reinforced denture base resin materials are presented in Fig. 3, Fig. 4, Fig. 5, and Fig. 6 respectively. SEM image analyses of the control group revealed that the base resin exhibited a brittle fracture under three-point bending test conditions.

It was observed from SEM images of the GF reinforced denture base resins that GFs had not been distributed homogeneously along the section of the specimen. PMMA matrix residues observed on the broken GFs' surfaces indicate that adhesive attachment between PMMA matrix and the GF surfaces occurred and fiber-matrix integration resulted a better strength under compressive load. Aggregation of the GFs within the PMMA matrix was reduced by increasing GF length. Denture base resins reinforced with 3- and 6-mm GFs exhibited relatively high local fiber aggregation than 12 mm GFs (Fig. 4A, B and C). Higher concentrations of GFs used resulted with denser GF clusters within the matrix (Fig. 4B, E and H).

SEM images revealed that all PPF reinforced groups exhibited a better fiber distribution compared to all GF reinforced groups (Fig. 5). Better interfacial matching (closeness of fitting) was observed for all PPF reinforced groups but weaker interfacial adhesion resulted with stripped PPFs from the opposite fracture pieces of test specimen (Fig. 5D and E). Ductile fracture was observed for longer PPFs used for reinforcement. Holes seen on SEM images (i.e. Figure 5H) formed by stripping of the PPFs due to load application during three-point bending test. The gap between the PPFs and the matrix (Fig. 5E) was formed by plastic deformation of PPF due to load application during three-point bending test. Random orientation of the PPFs due to dense and longer fiber use, they distributed along all directions and therefore enhance the flexural strength (Fig. 5I).

Almost perfect fiber distribution was present for CF reinforced groups (Fig. 6). This resulted with a perfect fracture interface. Increasing fiber lengths resulted with holes across the fracture surface but not as much as PPF reinforced groups (Fig. 6B). CFs were better distributed along the PMMA matrix and resulted with better interfacial interaction than both GF and PPF groups.

Discussion

In this study, glass fiber, polypropylene fiber and carbon fiber groups were set and added to heat-polymerized denture base resin with fiber to resin volume ratios of 0.25, 0.50 and 1.0% using 3, 6- and 12-mm long fibers for each group, and their effects on reinforcing of heat cured PMMA based denture base resins were evaluated. Flexural strengths by three-point bending tests and modulus of elasticity and ultimate tensile stress values by tensile tests were compared in order to determine the reinforcing effect.

Reinforcement using GF significantly enhanced the flexural strength compared to control group according to the three-point bending test results. This situation is parallel to the studies reported by Al-Thobity and Singh et al. in which flexural strength of the PMMA denture base resins were reinforced with GF[16, 26]. Yu et al. also reported enhancement of flexural strength by reinforcement with GF but they used a local placement and orientation of fibers[27]. Use of GF with 1.0 fiber to resin volume ratios for all fiber lengths resulted with a decrease in flexural strength, which can be explained by the increase in void space between fiber clusters formed by agglomeration of poorly distributed GFs. These void spaces between fibers caused discontinuity of the resin matrix and formation of weaker spots for enhancement of crack propagation during fracture. Similar to reinforcement with GF, reinforcement using PPF and CF significantly enhanced the flexural strength compared to control group. However,

reinforcement using PPF exhibited a higher flexural strength regardless of fiber length and concentration compared to reinforcement with GF. Concentration of fiber used did not cause a significant change in flexural strength for PPF reinforcement with any fiber length. Although no significance was obtained for PP fiber length and concentration on flexural strength, slight increase in flexural strength for reinforcement with short PPF by increasing concentration and a slight decrease in flexural strength for reinforcement with long PPF by increasing concentration was observed as it was reported by Mathew et al.[28]. It was observed during the three-point bending tests that the deflection of the resin samples decreased by increasing fiber lengths used for reinforcement. Consequently, it can be concluded that PMMA matrices reinforced with long PPFs fractured with lower deflection due to lack in maintaining the interfacial stability by distributing the compressive load appropriately on the fibers. Ismaeel et al. used PPFs which were surface modified with plasma application in order to enhance the mechanical properties of PMMA denture base resin by increasing the fiber matrix interfacial adhesion[29]. CF reinforced resin exhibited high flexural strength values comparing to control. Similarly, Ma and Chen reported greatest flexural strength by CF in their study that they compared GF, CF and Kevlar fibers on mechanical and thermal properties of PMMA composites[30]. Although good flexural strength values were obtained for resins reinforced using CFs, it is not possible to use these fibers for reinforcement of denture base resins for clinical use because of the dark grey color they provide to the denture base.

Despite the increase in modulus of elasticity of the resin reinforced by GF or CF fibers, using PPF for reinforcement decreased the modulus of elasticity. This should be expected because of the ductile character of the PPF. Ultimate tensile strength was observed to be greater for CF reinforced resin at 0.25% concentrations. This behavior may be explained by the better interfacial match, and possible physical and/or chemical bonding between the CF surface and PMMA matrix. And as a result of this, a better distribution of tensile load between matrix and fibers led the test specimen to resist higher tensile forces before fracture.

SEM analyses of GF reinforced groups revealed that the distribution of GFs along the PMMA matrix was not well even though they were observed to enhance the flexural strength. Therefore, processing the GF surface modification may enhance the interfacial match of GFs with PMMA matrix by physical/chemical bonding. PPFs were observed to be better distributed in the PMMA matrix but adhesion between the PPFs and the matrix was weak, so that fibers at the fracture plane were stripped from the opposite specimen parts by the load application. If the adhesion between the fiber and the PMMA matrix would be enhanced, mechanical properties could also be enhanced. PPF is a good reinforcing material for denture base resin since it increases the flexural properties and also non-toxic for the biological environment[31]. CFs were observed to be homogenously distributed within the PMMA matrix. Therefore, CF reinforced denture base resins were found to have the highest flexural strength. But the dark color provided by CFs to the PMMA matrix avoids its potential use as reinforcement of denture base resins.

Conclusion

In this study we aimed to determine and compare effects on mechanical properties using glass, polypropylene and carbon fibers with 3, 6- and 12-mm lengths, and 0.25, 0.50 and 1.0% concentrations (v/v) as reinforcement of PMMA denture base resins. All fibers were used without any treatment and volumetric concentrations were used in order to eliminate the errors originated from the different densities of the fiber material. All tests and analyses performed within this context revealed that all fiber types can enhance the mechanical properties such as flexural strength, modulus of elasticity. All three fibers exhibited reinforcement in flexural strength regardless of their length but concentration had significant effect. Although fiber-resin interaction was observed to be weaker than reinforcement using GF or CF, reinforcement with PPF provided quite good mechanical properties comparable with

reinforcement using GF or CF. Therefore, PPF reinforced denture base resin is concluded to be a promising material when cyclic loads such as chewing etc. in the mouth is considered. Enhanced interfacial adhesion and ductile character of surface modified/treated PPF may reveal outstanding results for the reinforcement of heat-cured PMMA denture base resins.

Abbreviations

%: Percent, **°:** Degree, **°C:** Centigrade degrees**, CF:** Carbon fiber, **g/cm^3:** Gram per cubic centimeter, **GF:** Glass fiber, **kV:** Kilovolt, **mm:** Millimeter, **mm/min:** Millimeter/minute, **MPa:** Megapascal, **PMMA:** Polymethyl methacrylate, **PP:** Polypropylene, **PPF:** Polypropylene fiber, **SEM:** Scanning electron microscope, **UTS:** Ultimate tensile stress; **v/v:** Volume/volume.

Declarations

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Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that “they have no competing interests”.

Authors Contribution

KY: Conceptualization, Methodology, Data Analysis, Writing and Editing

TBT: Visualization, Investigation

ÖE: Writing and Reviewing

SE: Conceptualization, Methodology, Data Analysis, Writing and Reviewing

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Figures

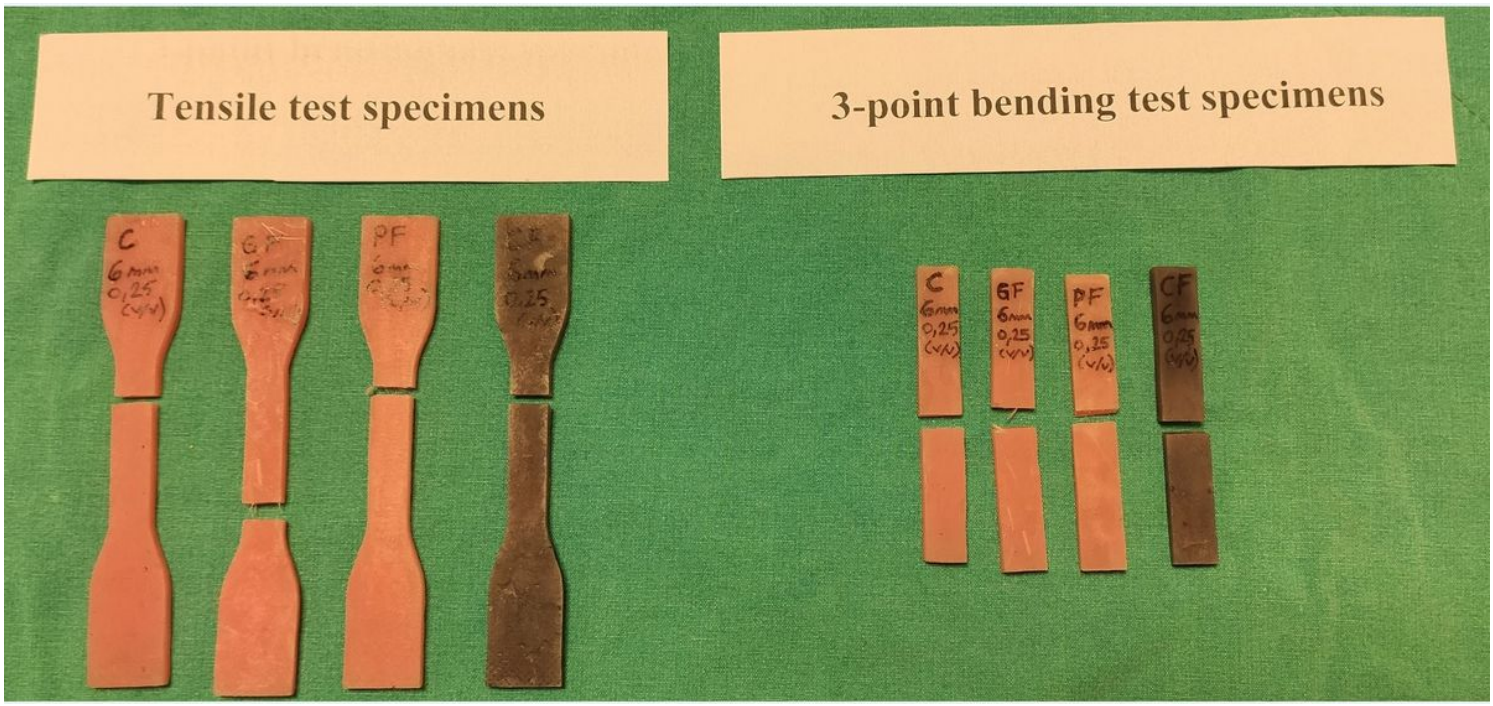

Figure 1

Test specimens after three point bending and tensile tests.

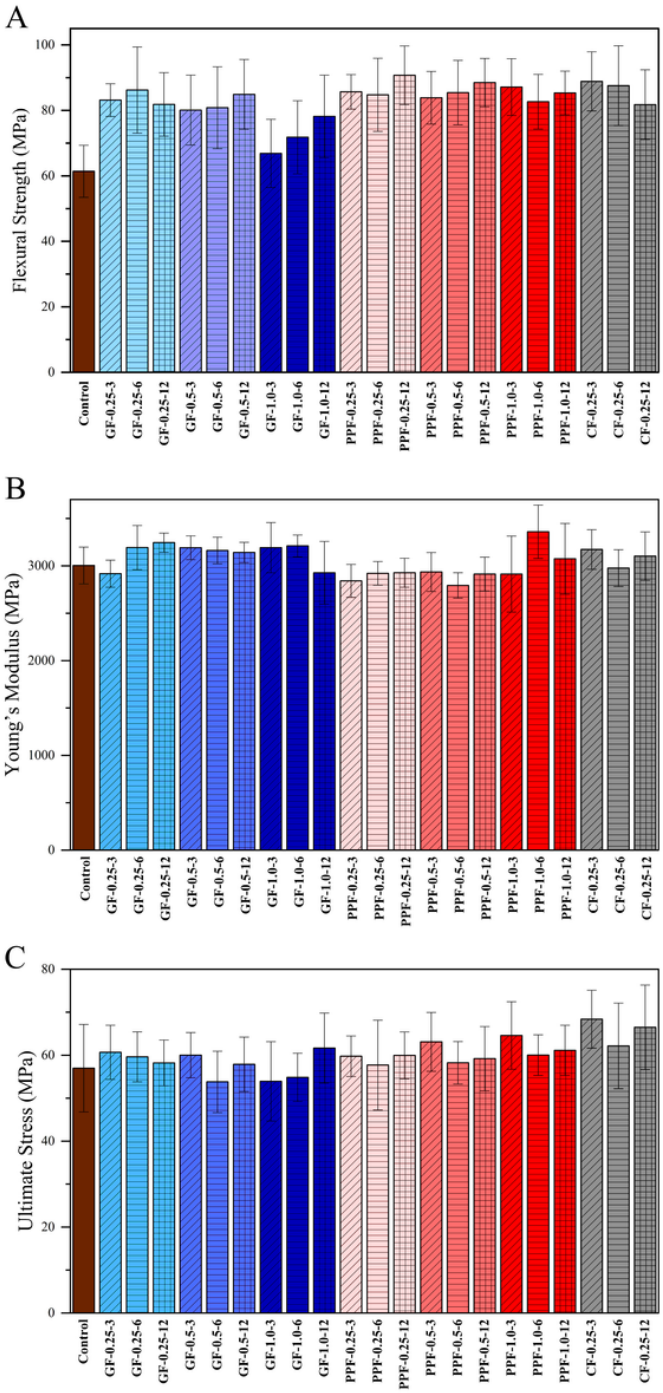

Figure 2

Graphs of; A) Flexural strength (by three point bending test); B) Modulus of elasticity (Young's modulus by tensile test); C) Ultimate tensile strength (by tensile test)

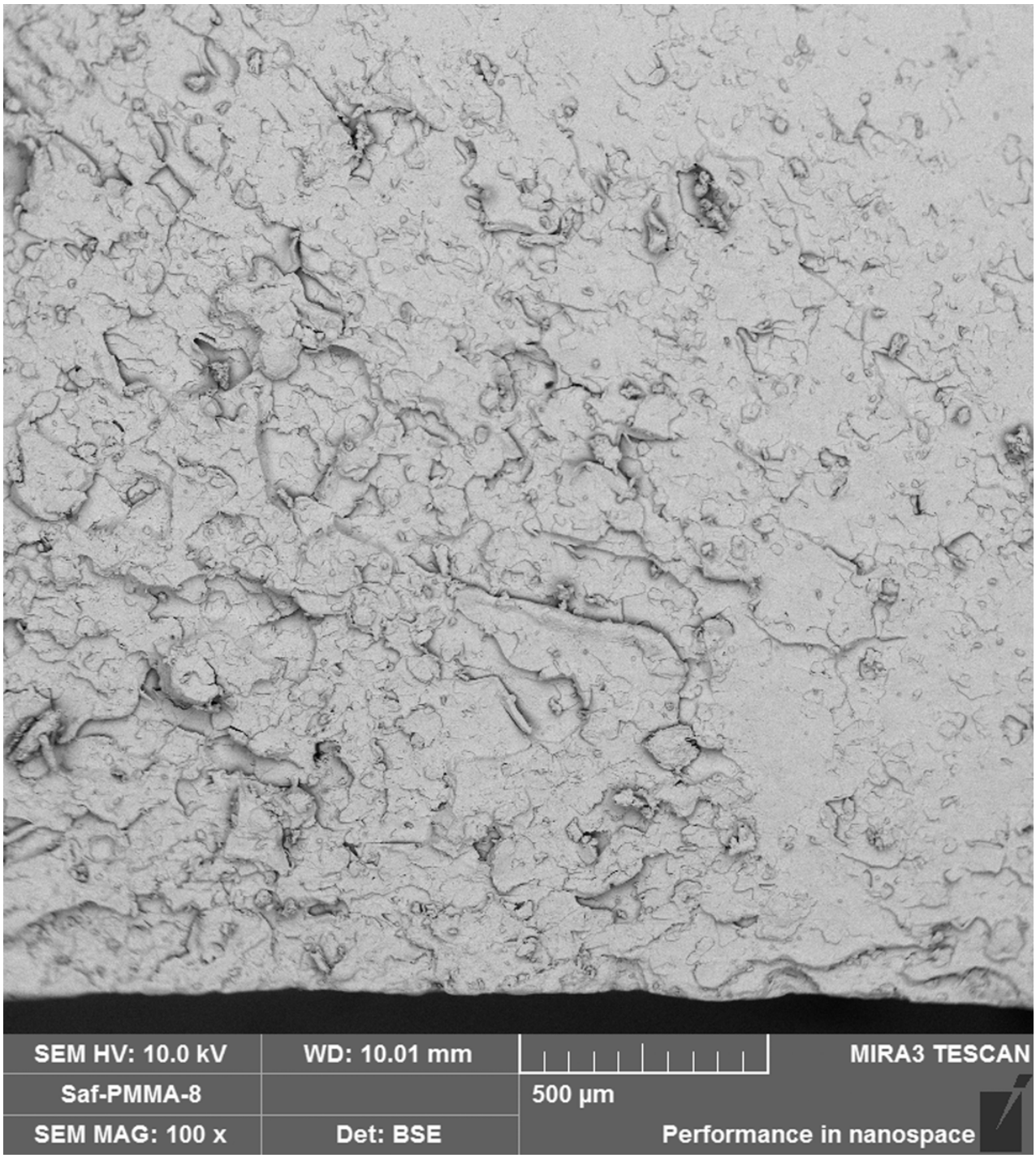

Figure 3

100x SEM image taken from the fracture surface of the control group.

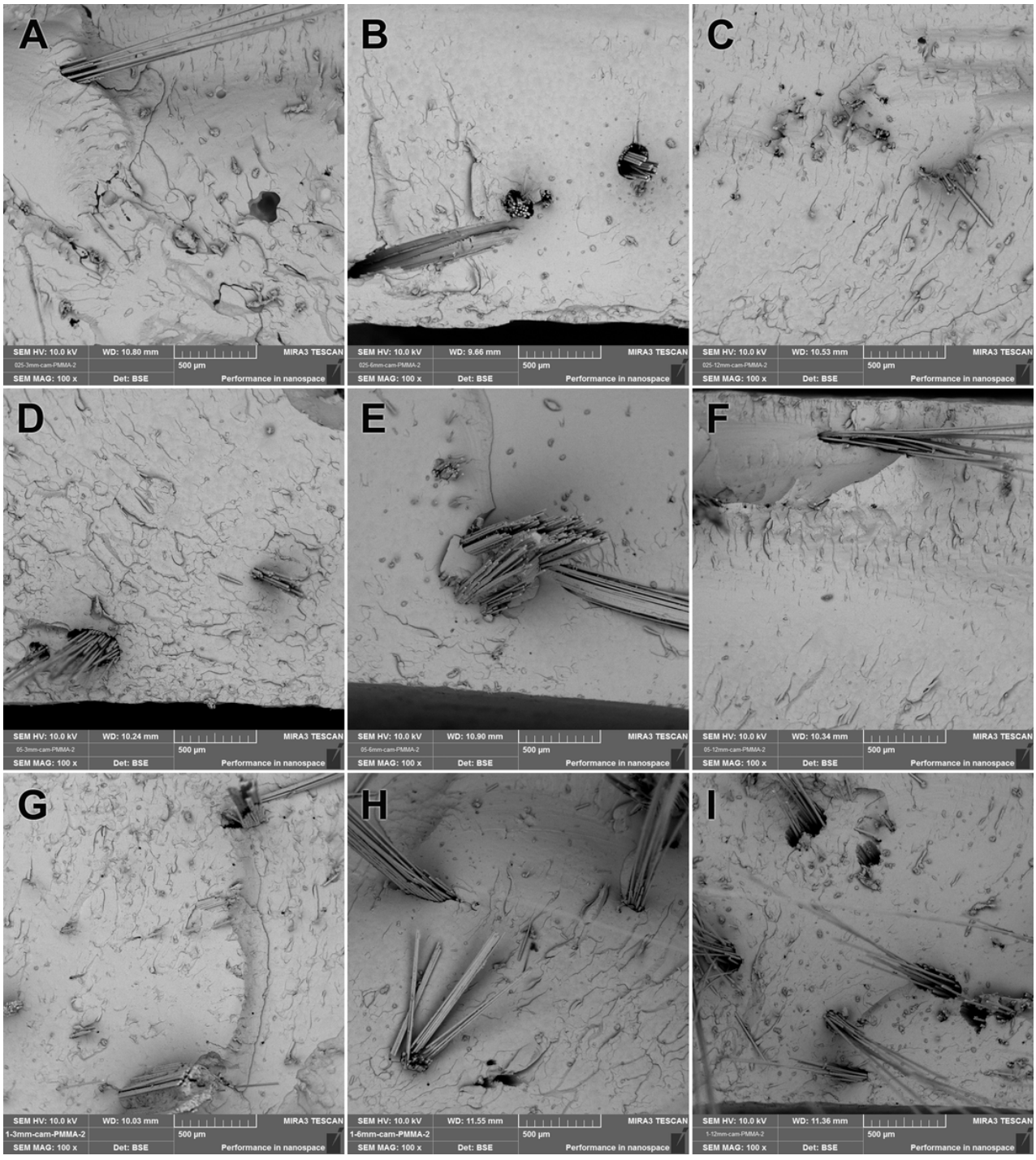

Figure 4

100x SEM image taken from the fracture surface of the GF group; A: GF-0.25-3; B: GF-0.25-6; C: GF-0.25-12; D: GF-0.50-3; E: GF-0.50-6; F: GF-0.50-12; G: GF-1.0-3; H: GF-1.0-6; I: GF-1.0-12.

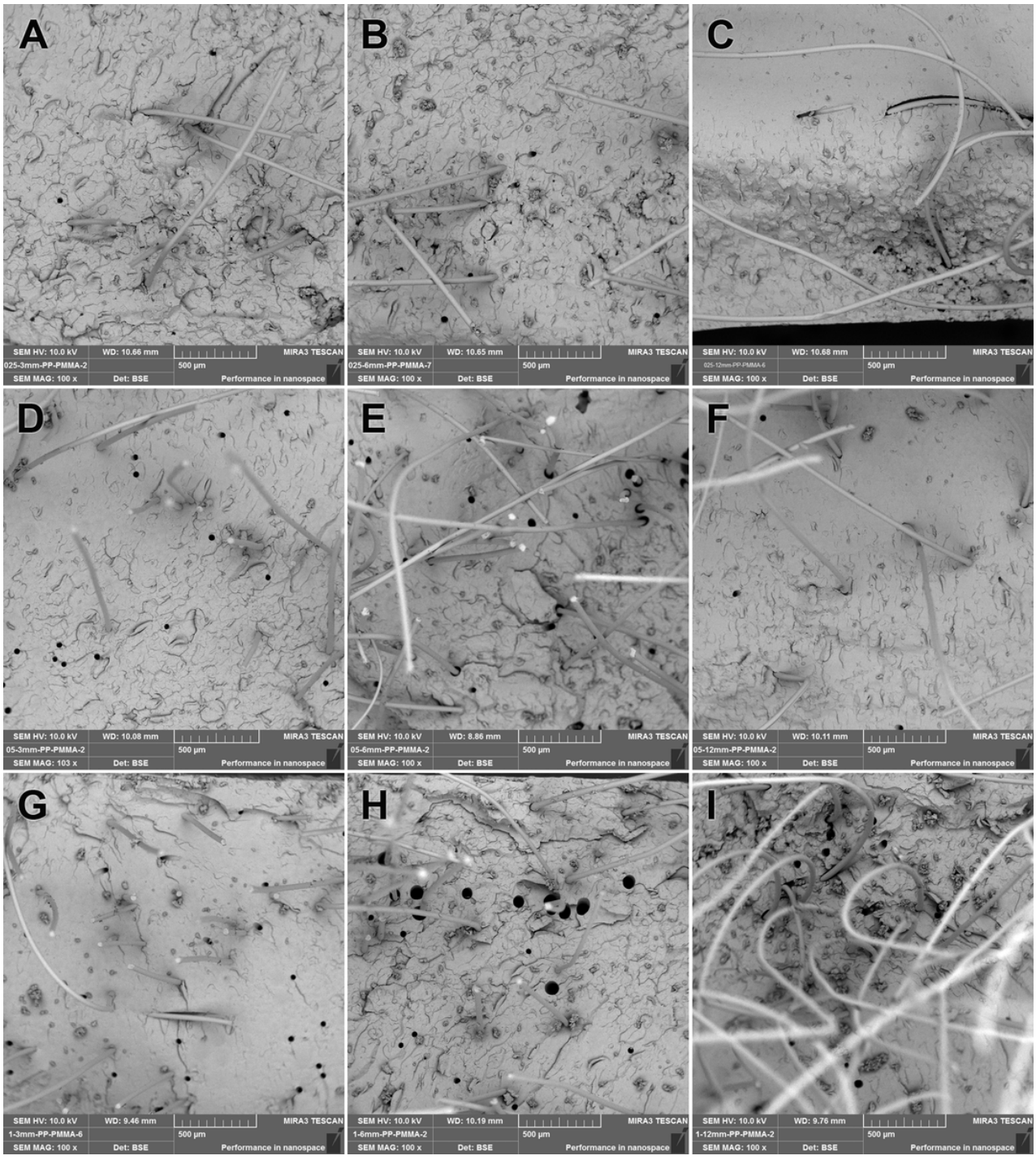

Figure 5

100x SEM image taken from the fracture surface of the PPF group; A: PPF-0.25-3; B: PPF-0.25-6; C: PPF-0.25-12; D: PPF-0.50-3; E: PPF-0.50-6; F: PPF-0.50-12; G: PPF-1.0-3; H: PPF-1.0-6; I: PPF-1.0-12.

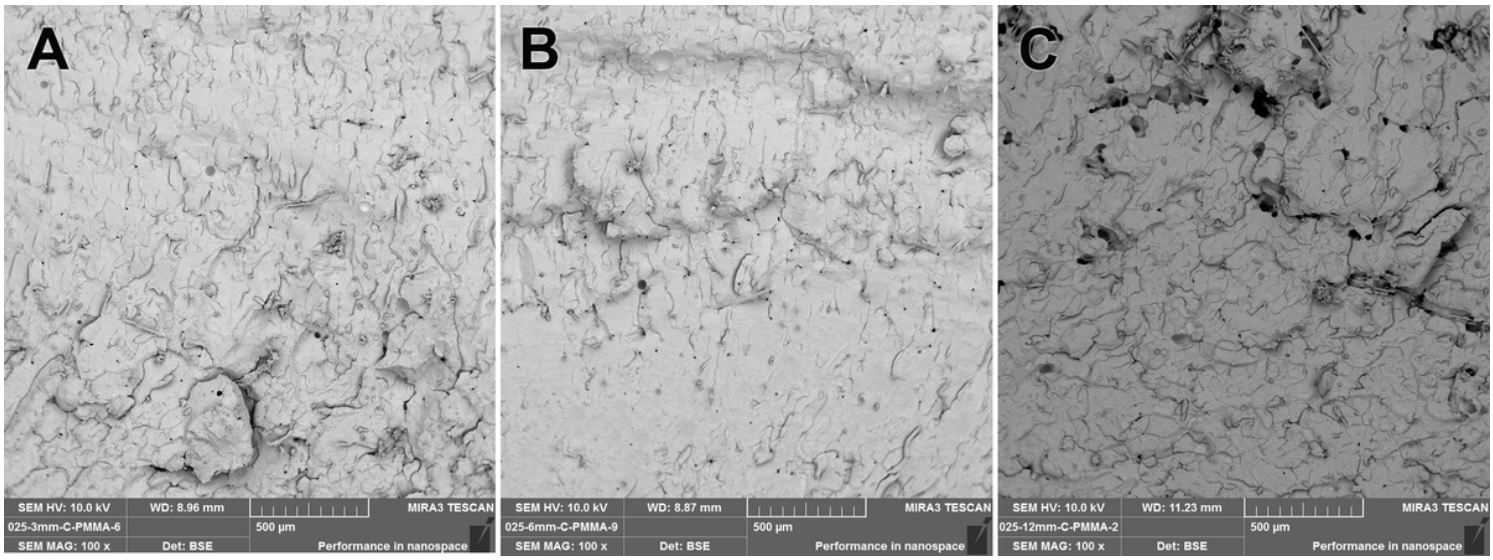

Figure 6

100x SEM image taken from the fracture surface of the CF group; A: CF-0.25-3; B: CF-0.25-6; C: CF-0.25-12.