

The effect of incorporating various reinforcement materials on flexural strength and impact strength of polymethylmethacrylate: A meta-analysis

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Abstract

Polymethylmethacrylate (PMMA) is a widely used denture base material with a major drawback of inferior mechanical properties. In the existing published reports, most studies indicate the superiority of the incorporation of various reinforcement materials in PMMA in terms of the flexural strength (FS) and impact strength (IS), whereas none shows the compilation and comparison of all. The present meta-analysis aims at synthesizing all the available data. The purpose of this study was to systematically review the existing reports to compare and evaluate the effect of various reinforcement materials on FS and IS of heat-cured acrylic resin (PMMA) by combining the available evidence in a meta-analysis. A search strategy was adopted using PubMed, ScienceDirect, Ebscohost, Google Scholar, and Cochrane Central Register of Controlled Trials in February 2018 to screen research studies. These studies were screened against predetermined criteria for eligibility for meta-analysis. In the present meta-analysis, twenty articles were included. Out of 15 data available on reinforcement, 14 showed better results for IS of reinforced PMMA resin as compared to their respective control group. Out of the 25 available data, 11 showed better results for FS of reinforced PMMA resin when compared to their respective control group. The homogeneity test of meta-analysis confirmed acceptable heterogeneity among 15 reinforcement techniques of IS ($i^2 = 95.8\%$) and 25 reinforcement techniques of FS ($i^2 = 96.2\%$). A random-effects model and fixed-effects model were used for analysis. The present meta-analysis showed that reinforcement of PMMA can significantly increase FS and IS. Hence, it can be incorporated in clinical practice.

Keywords: Acrylic resin, flexural strength, impact strength, polymethylmethacrylate, reinforcement

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Received: 26th September, 2018, **Accepted:** 03rd April, 2019

INTRODUCTION

Polymethylmethacrylate (PMMA) is the most commonly used denture base material for the past eight decades in the world of dentistry.^[1-14] Its excellent esthetic results and ease in manipulation and repair have majorly contributed for its

success. However, to overcome the deficiencies of PMMA resin, development and introduction of various polymers have been made. However, none satisfied the clinician in comparison to PMMA universally. This can be attributed to the fact that, though the properties of PMMA resin are

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How to cite this article: Somani MV, Khandelwal M, Punia V, Sharma V. The effect of incorporating various reinforcement materials on flexural strength and impact strength of polymethylmethacrylate: A meta-analysis. J Indian Prosthodont Soc 2019;19:101-12.

Access this article online	
Quick Response Code:	Website: www.j-ips.org
	DOI: 10.4103/jips.jips_313_18

not ideal in every aspect, it is the combination of various rather than one single desirable property.^[2,15]

The major drawback of PMMA is its inadequate mechanical and physical properties such as low flexural strength (FS), low impact strength (IS), and low surface hardness that leads to reduced clinical performance of the denture.^[3,6,7,16-22] This ultimately leads to reduced clinical life of the prostheses, and hence increases the patient's dental visits and the cost factor.

Dentures are known to undergo various failures such as fractures, de-bonding of the teeth, and other types of failures in complete or partial dentures.^[5] According to a survey conducted by Darbar *et al.* on the causes of repairs involving complete and partial dentures, it was reported that 29% of all repairs to dentures were associated with midline fractures of complete dentures.^[23] Therefore, there is a clear need to understand why such fractures occur and to find ways to reinforce the dentures to prevent such failures.^[5] A study by Johnston *et al.* showed that 68% of acrylic resin denture break within a few years after fabrication. This is caused primarily by impact failure when the denture is accidentally dropped on a hard surface or by fatigue failure when the denture base deforms repeatedly under occlusal force.^[4] In maxillary dentures, most fractures are caused by a combination of fatigue and impact, whereas in mandibular dentures, 80% of fractures are caused by impact. In most situations, fractures occur in the midline of the denture base.^[5,24] Fracture in this location occurs more often in maxillary dentures than in mandibular dentures.^[4,23] The modes of failure are flexural fatigue failures caused by occlusal biting force and impact force failures caused by dropping the denture.^[16]

To overcome these drawbacks, various approaches have been used. One approach is to increase its mechanical properties by the incorporation of a rubber phase in the bead polymer. Although this is a well-known method in plastic technology, it is expensive. The graft copolymers of rubber methacrylate produced by chemical modification are high-impact resins.^[1] Another approach used is by either modifying the composition or to devise a reinforcement of the denture base polymer with various reinforcement materials such as metal oxides, fibers, stainless steel wires, and mica. Many trials have been done to improve the strength of acrylic denture bases with the use of metal wires and cast metal plates. The main drawback with adding metal wire is weak bond between the wire and resin, which leads to insignificant change of mechanical properties. Although metal plates are expected to increase the strength, they are expensive and liable to corrosion. Other trials

have also been made to strengthen acrylic resin materials by introducing various organic and inorganic reinforcing fibers into them. Metal, Kevlar[®], glass, sapphire, polyester, carbon graphite, and rigid polyethylene are substances used for fiber strengthening. Reinforcement with fibers enhances the mechanical strength characteristics of denture bases, such as the transverse strength, ultimate tensile strength, and IS. In addition, fiber reinforcement has advantages compared with other reinforcement methods, including improved esthetics, enhanced bonding to the resin matrix, and ease of repair.^[4]

Although most of the available literatures confirmed the superior mechanical properties of reinforced PMMA, there are many studies contradicting the same. In addition, with the availability of various reinforcement materials, the choice of selection becomes difficult for the operator. Hence, an evidence-based study is required to know the effect of reinforced PMMA on both FS and IS.

There is enormous literature on various reinforcement materials and their effect on different properties, but according to the authors' knowledge, there is no single documentation on the compilation of all the reinforcement materials and their effect on various properties. The objectives of this meta-analysis review were to critically examine and compile the studies involving various reinforcement materials and determine the effect of these materials on FS and IS of PMMA.

Hence, the present meta-analysis was conducted to summarize various reinforcement materials and their effect on FS and IS.

MATERIALS AND METHODS

This review was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

Search strategy

All literatures that investigated the effect of reinforcement materials and their effect on the mechanical properties of PMMA were searched using the PRISMA statement guidelines with a predetermined search strategy. The search strategy was based on a population (heat-cured PMMA), intervention (different available reinforcement materials), comparison (unreinforced PMMA with reinforced PMMA), outcome (IS and FS), and study design (networking meta-analysis), i.e., PICOS framework [Table 1]. The search was done to include studies comparing IS and/or FS of reinforced and unreinforced heat-cured PMMA.

Search terminologies included PMMA, reinforcement, PMMA impact strength, PMMA flexural strength, and heat cure PMMA. An electronic search of studies published in PubMed (www.ncbi.nlm.nih.gov/entrez/query.fcgi), ScienceDirect (www.sciencedirect.com), Google Scholar (<http://scholar.google.com>), Cochrane Central Register of Controlled trials (http://www.mrw.interscience.wiley.com/cochrane/cochrane_clcentral_articles_fs.htm), and Ebscohost till March 2018 was included. Search terms were a combination of the appropriate Medical Subject Headings terms and free-text words in simple or multiple conjunctions and were grouped into PICOS.

Inclusion and exclusion criteria

Two reviewers read the titles and abstracts of the studies independently to decide whether the studies met the inclusion criteria. Full articles were examined if necessary. Any disagreement between the first two reviewers was resolved by third and fourth reviewers.

Inclusion criteria

- It should be an original study (*in vitro/in vivo*)
- It should be a complete study (full-text article)
- Study should be on heat-cured acrylic resin and/or reinforced heat-cured acrylic resin
- SI unit of IS must be in kJ/m² and/or convertible to the same
- SI unit of FS must be in MPa and/or convertible to the same
- Test methodology for FS should be 3-point bending test
- Test methodology for IS should be Charpy test and/or Izod test though it was not an exclusion criterion.

Exclusion criteria

- Review articles
- Incomplete studies
- Studies between different manufacturers of heat-cured materials
- Studies which measured FS and IS by incorporating other variables (such as water sorption)

Table 1: PICOS search strategy

PICOS	
P: Participants	Heat-cured acrylic resin
I: Interventions	Different reinforcement materials
C: Comparison	Heat-cured resins and heat-cured resins reinforced with various materials such as carbon, Kevlar, polyethylene fibers, metal wire, glass fiber, polyester fiber, titanium dioxide particles, silica, ultra-high modulus polyethylene fiber, polymethylmethacrylate fiber, metal oxides, E-glass fiber, halloysite nanotubes, nylon, etc.
O: Outcomes	Flexural strength and impact strength
S: Study design	Networking meta-analysis

- Studies without units and/or unconvertible units for FS (MPa) and IS (kJ/m²).

Quality assessment

Quality assessment was performed independently by two investigators using the Cochrane Collaboration tool for assessing risk of bias; any conflicts were discussed and resolved by another two authors. The tool contains two parts, addressing the seven specific domains (namely sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective outcome reporting, and other issues). An estimated risk of bias (low, medium, or high) was assigned to each of the included studies by the investigators. The disagreements were resolved by discussion between all the four authors.

Data extraction and statistical analysis

Data were extracted by two reviewers independently using a designed form that included the following information: year of publication, type of reinforcement, type of study, conditioning of reinforcement, conditioning of samples, test methodology, sample size for reinforced and control group, and FS (MPa) and/or IS (kJ/m²) of reinforced and control groups, respectively. Contact was made with authors whenever the data were missing or ambiguous. The studies in which the data were not clearly stated were excluded from the analysis.

Mean differences (MDs), a continuous outcome, were used to measure IS and FS. The level of significance was $P \leq 0.01$. Heterogeneity was assessed for the outcomes in each study and investigated using forest plots and the I^2 statistic. A random-effects model and a fixed-effects model were preferred for meta-analysis if statistically significant heterogeneity was identified among a group of studies. Publication bias was measured using visualization of funnel plots. Asymmetry of the funnel plot indicates publication bias and other biases related to the sample size.

RESULTS

A total of 9111 records were identified through database searching (PubMed, Ebscohost, and Google Scholar), out of which 8840 records were excluded as they were irrelevant or data were unavailable, or due to repetition. The remaining 271 full-text articles were assessed for eligibility, out of which 212 articles were excluded due to either of the following reasons: test material was cold cure, relining material, review articles, and studies between different heat-cured resins. Of the 59 full-text

articles selected for IS and/or FS, 39 full-text articles were excluded for the following reasons: values of interest in different units, hence cannot be compared (19); studies on different processing methods (5); studies with no units (4); studies on different sites of incorporation of material (7); and studies on the duration of water immersion (4). Thus, finally, twenty studies were included in the present meta-analysis [Figure 1].

Meta-analysis

The meta-analysis was performed by combining the results of the twenty studies which included 15 and 25 reinforcement techniques for IS and FS, respectively [Tables 2 and 3]. The homogeneity test confirmed acceptable heterogeneity among the studies ($I^2 = 96\%$). A random-effects model and fixed-effects model were used.

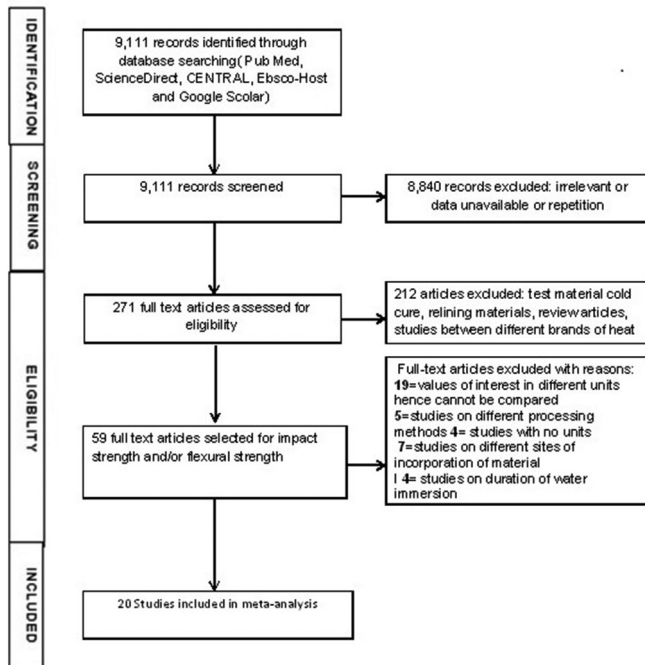


Figure 1: Literature search flowchart

The results of IS demonstrated statistically significant heterogeneity with $Q = 329.42$ and $df = 14$, with $P < 0.0001$. We thus used the random-effects model and fixed-effects model. For fixed-effects model, the MD was 0.83 (95% confidence interval [CI] = 0.69; 0.98). For the random-effects model, the estimated MD was 2.1348 and the 95% CI was 1.3556; 2.9140, which indicates a statistically significant difference between the treatment and control groups in terms of IS of the reinforcement materials. Among the 15 studies, 14 yielded statistically significant results. The difference was highest in reinforcement study 14 [Figures 2 and 3].

The results of FS demonstrated statistically significant heterogeneity with $Q = 626.83$ and $df = 24$, with $P < 0.0001$. For fixed-effects model, the estimated MD was 0.3777 and the 95% CI was 0.2564; 0.4989. For the random-effects model, the estimated MD was -0.2460 and the 95% CI was -0.9367 ; 0.4447, which indicates a statistically significant difference between the treatment and control groups in terms of FS of reinforcement materials. Among the 25 studies, 24 yielded statistically significant results. The difference was highest in reinforcement study 25 [Figures 4 and 5].

These results indicate that incorporation of reinforcement in PMMA can significantly increase its IS and/or FS. A visual inspection of the funnel plots showed no clear asymmetry, indicating the possible absence of publication bias. However, considering the small number of studies included in the meta-analyses, publication bias was given the low power of the statistical tests.

DISCUSSION

PMMA is the most commonly used denture base material, which has survived the introduction of various alternative materials such as polycarbonates and polyamides. It

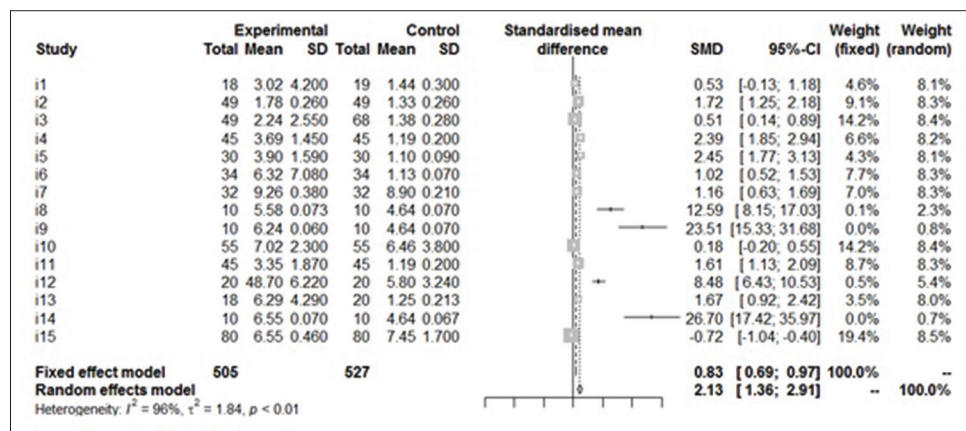


Figure 2: Forest plot for comparison of impact strength of various reinforcement groups with nonreinforced polymethylmethacrylate

Table 2: Comparison of mean values of impact strength of various reinforcement groups with nonreinforced polymethylmethacrylate as stated in the included studies

Code	Type of reinforcement	References	Type of study	Conditioning of reinforcement	Dimensions of samples (mm ³)	Conditioning of samples	Test methodology	Impact strength			
								Sample size for reinforced group	Impact strength of reinforced group (kJ/m ²)	Sample size for control group	Impact strength of control group (kJ/m ²)
i1	Glass fiber	Uzun <i>et al.</i> , 1999 ^[1] Kanie <i>et al.</i> , 2000 ^[17]	<i>In vitro</i> <i>In vitro</i>	Conditioned Conditioned	60×10×4 40×4×3	- -	Charpy test Fly wheel-type impact testing machine	9 9	14.959 1.691	10 9	1.246 1.4662
i2	Glass fiber	Kanie <i>et al.</i> , 2000 ^[17]	<i>In vitro</i>	Unconditioned	40×4×3	-	Fly wheel-type impact testing machine	9	1.731055556	9	1.4662
i3	Glass fiber	Chen <i>et al.</i> , 2001 ^[10] Kanie <i>et al.</i> , 2000 ^[17]	<i>In vitro</i> <i>In vitro</i>	Unconditioned -	63.5×12.75×10 40×4×3	- Wet	Charpy test Fly wheel-type impact testing machine	40 18	1.8325 1.711027778	40 18	1.19 1.4662
i4	Kevlar fibers	Chen <i>et al.</i> , 2001 ^[10]	<i>In vitro</i>	-	63.5×12.75×10	Wet	Charpy test	40	1.8325	40	1.19
i5	Kevlar fibers	Uzun <i>et al.</i> , 1999 ^[1]	<i>In vitro</i>	Conditioned	60×10×4	Wet	Charpy test	18	6.29285	20	1.246
i6	Polyethylene	Chen <i>et al.</i> , 2001 ^[10]	<i>In vitro</i>	unconditioned	63.5×12.75×10	Dry	Izod test	45	3.688888889	45	1.19
i7	Polyethylene	Gutteridge, 1992 ^[25]	<i>In vitro</i>	Unconditioned	50×6×4	Wet	Zwick pendulum test	30	3.9	30	1.1
i8	Zirconium oxide	Gutteridge, 1992 ^[25]	<i>In vitro</i>	Conditioned	50×6×4	Wet	Zwick pendulum test	24	3.175	24	1.1
i9	Zirconium oxide	Uzun <i>et al.</i> , 1999 ^[1] Ihab and Moudhaffar, 2011 ^[12]	<i>In vitro</i> <i>In vitro</i>	Conditioned Conditioned	60×10×4 80×10×4	Wet Wet	Charpy test Charpy test	10 32	18.877 9.255	10 32	1.246 8.9
i10	Titanium oxide	Asar <i>et al.</i> , 2013 ^[7]	<i>In Vitro</i>	Unconditioned	50×6×4	Wet	Drop tower impact test machine	10	6.5536	10	4.64
i11	Aluminum oxide	Asar <i>et al.</i> , 2013 ^[7]	<i>In vitro</i>	Unconditioned	50×6×4	Wet	Drop tower impact test machine	10	5.5846	10	4.64
i12	PMMA fibers	Asar <i>et al.</i> , 2013 ^[7]	<i>In vitro</i>	Unconditioned	50×6×4	Wet	Drop tower impact test machine	10	6.2351	10	4.64
i13	Steel wire	Jagger <i>et al.</i> , 2001 ^[8] Jagger <i>et al.</i> , 2001 ^[8]	<i>In vitro</i> <i>In vitro</i>	Conditioned Conditioned	50×6×4 50×6×4	Wet Wet	Charpy test Charpy test	40 15	6 11.1	40 15	4.95 12.5
i14	Polyester	Vallittu <i>et al.</i> , 1995 ^[26]	<i>In vitro</i>	Conditioned	50×6×4	Wet	Charpy test	20	48.7	20	5.8
i15	SWCNT	Chen <i>et al.</i> , 2001 ^[10] Qasim <i>et al.</i> , 2012 ^[27]	<i>In vitro</i> <i>In vitro</i>	Unconditioned Conditioned	63.5×12.75×10 25×2×2	Dry Wet	Izod test Charpy test	45 80	3.353 6.55125	45 80	1.19 7.45

SWCNT: Single-wall carbon nanotube, PMMA: Polymethylmethacrylate

Table 3: Comparison of mean values of flexural strength of various reinforcement materials with nonreinforced polymethyl methacrylate as stated in the included studies

Code	Type of reinforcement	References	Type of study	Conditioning of reinforcement	Dimensions of samples	Flexural strength					
						Conditioning of samples	Test methodology	Sample size for reinforced group	Flexural strength of reinforced group (MPa)	Sample size for control group	Flexural strength of control group (MPa)
S1	Glass fiber	Kanie et al., 2000 ^[7] Uma Maheswari et al., 2013 ^[28] Hamouda and Beyari, 2014 ^[29] John et al., 2001 ^[30]	<i>In vitro</i>	Conditioned	40 mm×4 mm×4 mm	-	3-point bend test	12	129.55	12	115.275
								60	136.87	60	91.32
								10	139.6	10	128.7
								10	979.2	10	696
								12	127.85	12	115.275
S2	Glass fibers	Kanie et al., 2000 ^[7] Singh et al., 2016 ^[28]	<i>In vitro</i>	Unconditioned	40 mm×4 mm×4 mm	-	3-point bend test	30	63.83333333	30	53.96
								24	128.7	24	115.275
								60	136.87	60	91.32
								30	63.83333333	30	53.96
								10	139.6	10	128.7
S3	Glass fiber	Kanie et al., 2000 ^[7] Uma Maheswari et al., 2013 ^[28]	<i>In vitro</i>	-	40 mm×4 mm×4 mm	Wet	3-point bend test	60	136.87	60	91.32
								60	136.87	60	91.32
								60	136.87	60	91.32
								60	136.87	60	91.32
								60	136.87	60	91.32
S4	Glass fiber	Hamouda and Beyari, 2014 ^[29] John et al., 2001 ^[30]	<i>In Vitro</i>	-	65 mm×10 mm×2.5 mm	Dry	3-point bend test	10	139.6	10	128.7
								10	979.2	10	696
								54	153.3688889	54	92.52
								15	91.33	15	96
								25	85.6	25	96
S5	E-glass fiber	Mathew et al., 2014 ^[32]	<i>In vitro</i>	Conditioned	60 mm×10 mm×2.5 mm	Dry	3-point bend test	15	91.33	15	96
								25	85.6	25	96
								15	81	15	96
								25	91.8	25	96
								8	62	8	90
S6	Polyethylene	Ladizesky et al., 1993 ^[33]	<i>In Vitro</i>	Conditioned	210 mm×12 mm×0.25 mm	-	3-point bend test	8	62	8	90
								40	110.135	40	85.54
								8	60	8	90
								8	113.5	8	128.7
								8	82	8	90
S7	Polyethylene	Ladizesky et al., 1993 ^[33]	<i>In vitro</i>	Unconditioned	210 mm×12 mm×0.25 mm	-	3-point bend test	25	85.6	25	96
								15	81	15	96
								25	91.8	25	96
								8	62	8	90
								40	110.135	40	85.54
S8	Polyethylene	Ladizesky et al., 1993 ^[33]	<i>In vitro</i>	-	210 mm×12 mm×0.25 mm	Wet	3-point bend test	8	62	8	90
								40	110.135	40	85.54
								8	60	8	90
								8	113.5	8	128.7
								8	82	8	90
S9	Polyethylene	Ladizesky et al., 1993 ^[33]	<i>In vitro</i>	-	210 mm×12 mm×0.25 mm	Dry	3-point bend test	25	91.8	25	96
								15	81	15	96
								25	91.8	25	96
								8	62	8	90
								40	110.135	40	85.54
S10	Zirconium oxide	Kul et al., 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	62	8	90
								40	110.135	40	85.54
								8	60	8	90
								8	113.5	8	128.7
								8	82	8	90
S11	Zirconium oxide	Ahmed and Ebrahim, 2014 ^[18]	<i>In vitro</i>	Unconditioned	50 mm×30 mm×30 mm	Dry	3-point bend test	8	60	8	90
								8	60	8	90
								8	113.5	8	128.7
								8	82	8	90
								8	82	8	90
S12	Titanium oxide	Kul et al., 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	60	8	90
								8	60	8	90
								8	113.5	8	128.7
								8	82	8	90
								8	82	8	90
S13	Titanium oxide	Hamouda and Beyari, 2014 ^[29]	<i>In Vitro</i>	Unconditioned	65 mm×10 mm×2.5 mm	Dry	3-point bend test	8	113.5	8	128.7
								8	113.5	8	128.7
								8	113.5	8	128.7
								8	113.5	8	128.7
								8	113.5	8	128.7
S14	Aluminum oxide	Kul et al., 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	82	8	90
								8	82	8	90
								8	82	8	90
								8	82	8	90
								8	82	8	90

Contd...

Table 3: Contd...

Code	Type of reinforcement	References	Type of study	Conditioning of reinforcement	Dimensions of samples	Flexural strength					
						Conditioning of samples	Test methodology	Sample size for reinforced group	Flexural strength of reinforced group (MPa)	Sample size for control group	Flexural strength of control group (MPa)
S15	Aluminum oxide	Elakwa <i>et al.</i> , 2008 ^[35]	<i>In vitro</i>	Unconditioned	65 mm×10 mm×3 mm	Dry	3-point bend test	60	124.8775	60	99.45
S16	Silver	Kul <i>et al.</i> , 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	82	8	90
S17	SiC	Kul <i>et al.</i> , 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	88	8	90
S18	SiC-Nano	Kul <i>et al.</i> , 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	44	8	90
S19	Si3n4	Kul <i>et al.</i> , 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	62	8	90
S20	Hydroxyapatite	Kul <i>et al.</i> , 2016 ^[34]	<i>In vitro</i>	Conditioned	50.8 mm×3 mm circular	Wet	3-point bend test	8	46	8	90
S21	Halloysite nanotubules	Abdallah, 2016 ^[14]	<i>In vitro</i>	Unconditioned	65 mm×10 mm×3 mm	Wet	3-point bend test	20	72.515	20	95.77
S22	SWCNT	Qasim <i>et al.</i> , 2012 ^[27]	<i>In vitro</i>	Conditioned	50 mm×6 mm×4 mm	Wet	3-point bend test	80	96.575	80	95.5
S23	Nylon	John <i>et al.</i> , 2001 ^[30]	<i>In vitro</i>	Conditioned	65 mm×10 mm×3 mm	Dry	3-point bend test	10	733.4	10	696
S24	Nylon	Singh <i>et al.</i> , 2016 ^[31]	<i>In vitro</i>	Unconditioned	65 mm×10 mm×3 mm	Dry	3-point bend test	10	59.37	10	53.96
S25	Aramid	John <i>et al.</i> , 2001 ^[30]	<i>In vitro</i>	Conditioned	65 mm×10 mm×3 mm	Dry	3-point bend test	10	849.9	10	696

SWCNT: Single-wall carbon nanotube

has a combination of both favorable and unfavorable properties.^[8] Therefore, many attempts have been made to enhance these properties by modifying the chemical structure of resin or by the addition of reinforcement materials.^[11,12,36-38]

Various methods have been tried to reinforce the acrylic resin denture bases. Metal inserts have been used in the form of wires, metal oxides, metal strengtheners, meshes, and plates, and the different fibers include Kevlar, glass, carbon graphite fibers, aramid fiber, ultra-high-molecular-weight polyethylene fiber, and polyethylene fibers to improve its mechanical properties.

To the authors' knowledge, this is the first meta-analysis of the effect of various reinforcement materials on the IS and FS of PMMA. The result of this meta-analysis suggested that most of the reinforcement materials used

in the past can significantly increase both IS and FS of PMMA. Furthermore, the effect of reinforcement was found to be affected by various factors including the size, shape, concentration, adhesion, and distribution of filler particles in the polymer matrix and strong adhesion at the interface.^[8,19,30,31] Strengthening by fiber reinforcement is based on the principle that polymer matrix is fully capable of transferring an applied load to fibers via shear forces at the interface. Fibers used for reinforcement act as the main load-bearing constituents, and the matrix forms a continuous phase to surround and hold the fibers in place.^[31] Fibers used should be stiff to reinforce the brittle material; otherwise, it will have little or no effect on the properties. Adequate adhesion of the fibers to the polymer is the most important variable for the strength of the composite so that stresses can be transferred from the matrix to the fibers. Silane coupling agent can be used to improve the adhesion.^[19] Effective impregnation allows the resin matrix to come into contact with the surface of every fiber and thus bonding is improved. Concentration of the fiber, when increased judiciously, considerably affects the properties of PMMA, but increased concentration may induce voids.^[31]

Addition of metal oxides improved some physical and mechanical properties of acrylic resin.^[7,39,40] The unpleasant discoloration that occurred even with the inclusion of a small percentage of metal indicated that the use of metal-filled PMMA should be in areas where it is not seen. The strength of these reinforced PMMA might allow their use in the posterior occlusal regions to withstand chewing stresses. Even with this apparent discoloration, which restricts the use of metal-filled resin to the palatal portion

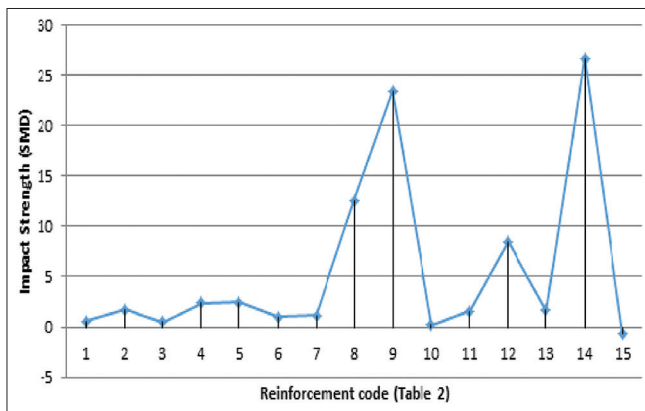


Figure 3: Graphical representation of standardized mean difference (SMD) values of impact strength

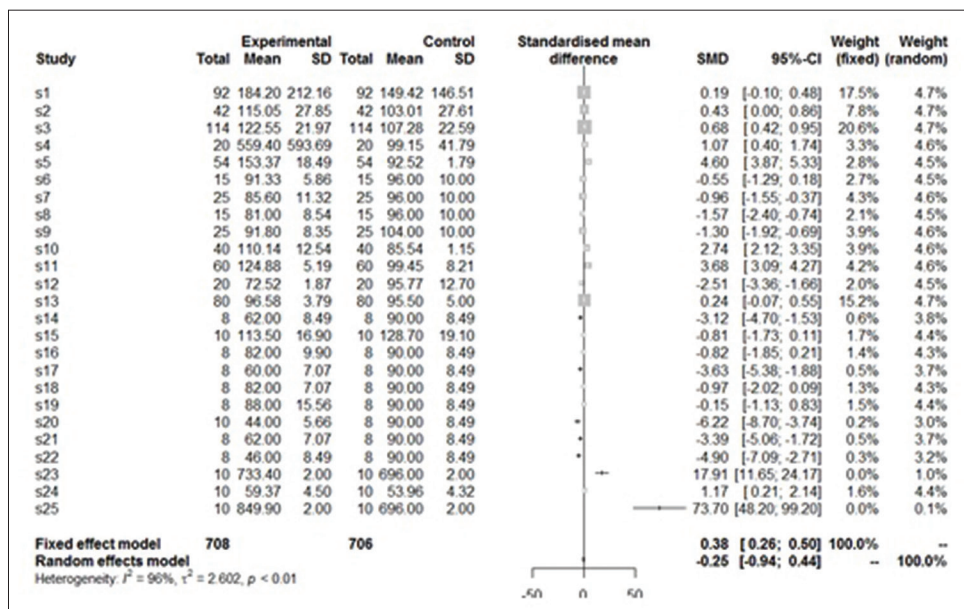


Figure 4: Forest plot for flexural strength of various reinforcement groups with nonreinforced polymethylmethacrylate

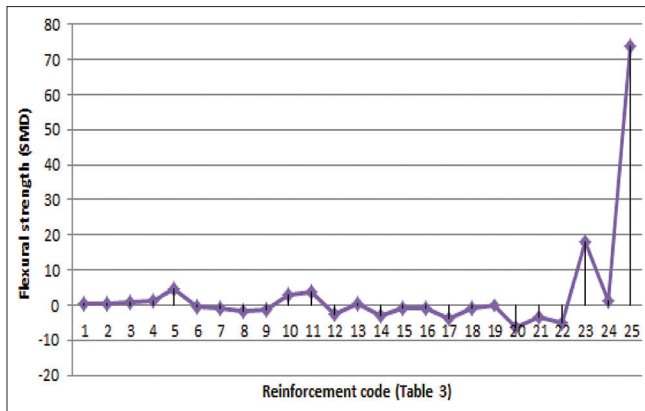


Figure 5: Graphical representation of SMD values of flexural strength

of upper and/or lingual flanges of lower dentures, the metal reinforcement is, nevertheless, likely to reduce the fracture incidence of acrylic denture.^[41] A marked gradual decrease was noticed in the tensile strength as the filler ratio increased which, in turn, limits the addition of fillers >5% by volume.^[39]

The particle size is another factor; larger particles decreased the tensile strength because they settle when mixed with monomer. The average particle size was 10 μm to match the particle size of resin powder, which permits the use of a conventional method in finishing the specimens.^[41]

The present meta-analysis is in line with the previous literature that has generally reported that reinforcement of PMMA leads to significant improvement in the mechanical properties of PMMA.^[1,4,10,11,16,19,30]

Forest plot for the effect of various reinforcement materials on IS showed that all the reinforcement materials included in the studies comparing the IS had showed significantly higher values than unreinforced PMMA except single-walled carbon nanotubes. Polyester fibers had showed the highest IS followed by zirconium oxide, PMMA fibers, Kevlar fibers, glass fibers, steel wire, aluminum oxide, polyethylene fibers, and titanium oxide [Figure 2].

Whereas the forest plot for the effect of various reinforcement materials on FS showed that not all the reinforcement materials included in the studies comparing the FS showed superior result. Aramid fibers showed the highest value followed by nylon fibers, E-glass fibers, zirconium oxide, glass fibers, and titanium oxide, which showed significantly better result when compared to the unreinforced PMMA. Whereas Si_3N_4 , polyethylene fibers, silver particles, SiC nano particles, aluminum oxide, halloysite nanotubes, SiC particles, carbon nanotubes, and hydroxyapatite showed inferior result [Figure 4].

Studies on the effect of reinforcement on both IS and FS were available with zirconium oxide, glass fibers, titanium oxide, aluminum oxide, polyethylene fibers, and carbon nanotubes. Among these, zirconium oxide, glass fibers, and titanium oxide showed improvement in both IS and FS, while aluminum oxide and polyethylene fibers showed increase in IS but reduced FS when compared with unreinforced PMMA. Carbon nanotube reinforcement exhibited decrease in both IS and FS. Studies on reinforcement with other materials evaluated either of the properties.

Glass fibers have gained popularity as a reinforcing agent of PMMA because of their good esthetic qualities and good bonding to polymer via silane coupling agent. The preimpregnation makes the glass fiber easy to use and the fiber does not fray and can be placed in the desired region of the prosthesis. Glass fiber is shown to improve the mechanical properties, especially fatigue resistance, transverse strength, IS, and FS, but has no significant effect on the bending strength and surface hardness.^[1,4,10,30,29,42] This can be attributed to good adhesion of the glass fibers to denture base polymer which transfers the stress applied to the matrix to the fibers, hence the low percentage of elongation at breakage of glass fibers.^[31] Another advantage is that, if the prosthesis fractures catastrophically, then the fractured portions are likely to remain in close proximity, held together by the fibers.^[10]

Zirconia is a bio-compatible material that possesses high fracture resistance and improved fracture toughness. Addition of Zirconia nano fillers to acrylic resin was found to improve the mechanical properties of PMMA.^[12,13] Studies showed significant increase in FS, fracture toughness, and hardness as the percentage of ZrO_2 fillers increased. In addition to that, ZrO_2 was used because it has excellent biocompatibility and white color which is less likely to alter esthetics.^[13] The nano-filler particles yield a better dispersion, eliminate aggregation, and improve its compatibility with organic polymer.^[13] This improvement in mechanical properties could be attributed to the high interfacial shear strength between the nano filler and resin matrix as a result of the formation of cross-links or supramolecular bonding which covers or shields the nano fillers which, in turn, prevent propagation of crack, and also complete wetting of the nano fillers by resin leads to increase in FS, fracture toughness, and hardness as the volume of filler increases.^[13,41]

Further, the increase in transverse strength can be explained on the basis of transformation toughening. When sufficient stress develops and a crack begins to propagate, a transformation of ZrO_2 from the metastable

tetragonal crystal phase to the stable monoclinic phase occurs which depletes the energy of crack propagation. Furthermore, in this process, expansion of ZrO_2 crystals occurs and places the crack under a state of compressive stress, and crack propagation is arrested. Both mechanisms improve fracture resistance of denture base under applied mastication loads.^[43]

Titanium dioxide (TiO_2) is a naturally occurring white-colored mineral. This is highly biocompatible. Studies have shown that TiO_2 fillers resulted in significant increase in IS and fracture toughness and significant decrease in water sorption and solubility; modification of heat-cured acrylic resins with certain amounts of metal oxide may be useful in preventing denture fractures and undesirable physical changes resulting from oral fluids clinically.^[7]

In the present meta-analysis, reinforcement with aluminum oxide and polyethylene fiber reinforcement materials led to increase in IS but decrease in FS when compared to unreinforced PMMA. Aluminum oxide, commonly referred to as alumina, possesses strong ionic interatomic bonding, which can be the probable reason for increasing the IS.^[35,44]

Polyethylene fibers are claimed to enhance the physical properties of acrylic resin^[43] and are almost invisible in denture base acrylic resins.^[1] They have been found to increase the IS and modulus of elasticity.^[1,11,20,45,46] Highly drawn linear polyethylene fibers were recently developed and are having high stiffness and strength, proven biocompatibility, white translucent appearance, and negligible water sorption.^[33,47]

When short-length polyester fibers were added as resin strengtheners in a randomly oriented method, the denture can be processed easily by the traditional procedure without causing any esthetic problems. Use of polyester fibers has demonstrated multiple-fold improvement on IS,^[19] but had no significant effect on the bending strength and surface hardness.^[11]

Other reinforcing agents which improved the IS of PMMA were PMMA fibers, Kevlar fibers, and steel wire. The concept of self-reinforcement (a material which is chemically identical to the matrix holding the fibers in place) has been reported in the dental literature by Jagger and Harrison in 1999. A self-reinforced material was expected to have improved mechanical properties over the amorphous random polymer. The bond between fiber and matrix may influence the success of the reinforcement.^[8-10]

In 1973, DuPont introduced a para-aramid fiber called Kevlar. Addition of these fibers have significantly increased the IS,^[1] and modulus of elasticity of the resin. Although there is no significant effect on the bending strength and surface hardness, they are not used much because of their undesirable color and toxicity. They are also unesthetic, and therefore, their use is limited to certain intraoral applications.^[10,11,14,45]

Metal wires have been used as strengtheners but were found to be difficult to manipulate.^[10] The primary problem of using metal wire reinforcement is poor adhesion between wire and acrylic resin.^[4,17,48-52]

Other reinforcement agents which improved FS of PMMA were aramid fiber, nylon fibers, and E-glass fibers. Aramid fibers are resistant to chemicals, are thermally stable, and have a high mechanical stability, melting point, and glass transitional temperature, but they have poor esthetics and are difficult to polish.^[3,53,54]

Nylon fibers are polyamide fibers and are based primarily on aliphatic chains. Nylon fibers have been explored as esthetic fibers and are successfully used to match the minute blood vessels of oral mucosa.^[19] The chief advantage of nylon lies in its shock-absorbing resistance and resilience to repeated stress;^[19] however, its water absorption ability adversely affects its mechanical properties.^[19,30,31]

E-glass fiber is the most commonly used fiber for acrylic reinforcement due to its higher mechanical properties, low susceptibility to moisture absorption and hence relatively good long-term stability against water, resistance to chemicals, thermal stability and high melting point, and easy manipulation.^[32] They have better potential despite the difficulty of achieving adequate impregnation of the fibers.^[41] The study showed better FS when compared to unreinforced PMMA.^[19,32]

The present meta-analysis revealed that reinforcement with carbon nano tubes resulted in reduction of both IS and FS of PMMA. Other reinforcing agents including Si_3N_4 , silver particles, SiC particles, halloysite nano tubes, and hydroxyapatite showed inferior result for FS when compared to unreinforced PMMA.

Apart from reinforcement materials, milled PMMA-based dentures are considered a recent mode of advancement. They are claimed to be of better mechanical properties, and hence can be considered for future research and development.

This study cannot claim the superiority of any single reinforcement material as there are multiple variables, i.e., concentration, physical properties, and chemical properties, which were not included as these were not mentioned in most of the articles and hence were out of the scope for the authors. Due to lack of sufficient literature on the *in vivo* effect of the reinforced PMMA, the meta-analysis included all the *in vitro* studies. In addition, the present meta-analysis included very few articles; hence, bias must be considered as the main drawback. Many studies were excluded due to incomplete data, studies with different parameters, different procedures, and/or studies not falling in our inclusion criteria; hence, the total number of studies included were very few which can lead to bias. Furthermore, different concentrations of reinforcement were used by different authors, which can significantly affect the outcome.

Overall, this meta-analysis confirms the superiority of reinforced PMMA when compared to unreinforced PMMA in its mechanical properties. The authors suggest more *in vivo* studies to be done to know the clinical performance of reinforced PMMA, and also insist to work on standardization of these materials based on their physical and chemical composition along with a specific concentration for the best results. The authors have tried to include the maximum available studies on different reinforced PMMA resins and emphasize on the commercial development of these reinforcement materials.

CONCLUSION

This meta-analysis was an attempt to compile the maximum data available in literature on FS and IS of reinforced PMMA and converting all data to a common metric. Although a detailed mechanistic review is beyond the scope of this review, the following conclusions can be drawn:

- Fourteen reinforcement techniques out of 15 available data showed better results for IS of reinforced PMMA resin when compared to their respective control group
- Eleven reinforcement techniques out of 25 available data showed better results for FS of reinforced PMMA resin when compared to their respective control group
- Out of all the reinforcement materials included in the studies, zirconium dioxide, glass fibers, and titanium oxide showed increased values with respect to both IS and FS when compared to the unreinforced PMMA
- Hence, to increase the clinical life of PMMA, these reinforcement materials can be taken into consideration according to clinical requirement, patient's need, and clinician and laboratory personnel's skill.

Acknowledgment

The authors would like to thank Dr. Prashant Joshi, Professor and Head, MBA program, Dean, Faculty of Commerce and Management, Uka Tarasadia University, India, for his contribution in statistical analysis.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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