Mechanical Properties of Dental Restorative Composite Materials: A Review

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The objective of this present article is to review and appraise the method to determine fracture; deformation wears resistance of dental resin composite in an attempt to suggest the method and properties for investigations. This study aims to investigate the effect of different resin fillers and monomers currently available on mechanical properties and physical properties. The hybrid dental composites also contribute significantly to increasing the mechanical and tribological properties. Silane-treated filler improved the dental composite bonding strength. It is further revealed that the mechanical properties of the dental composite were improved by adding filler as well as by providing silane treatment to filler to increase the adhesion properties between resin and filler.

Keywords: Dental resin composite, Tribological properties, Mechanical properties.

2021. In Prashant Singh Rana, Deepak Bhatia & Himanshu Arora (eds.), *SCRS Proceedings of International Conference of Undergraduate Students*, 65–73. Computing & Intelligent Systems, SCRS, India. https://doi.org/10.52458/978-81-95502-01-1-7

1. Introduction

Resin-based dental composites were developed due to the unaesthetic and toxic nature of amalgam-based restorative material. Fiber-based restorative composites exhibit high strength and wear resistance according to the shape and size of fillers reinforcement [1]. Dental amalgam (Ag+Sn+Cu+Hg 50%) consists of mercury which has hazards on environmental health issues. Mechanical strengthening is an essential property for any dental restorative or prosthetic material, as well as natural teeth. Mechanical strengthening in the oral cavity is an essential quality for any dental restoration material, even for natural teeth. it is hoped that its extended duration should be the whole life of the patient. Thus, the experimentation and composition of such material are highly clinically applicable. In support of this statement is the fact that Fracture is a major cause of premature failure of any dental restorative material [2]. Though the occurrence of these failures is not rampant and its frequency may not even be greater than that for dental amalgam, enhancement of the fracture resistance properties of these materials is constantly being sought and if attained would likely enhance the longevity of dental composite restorations. While a standard methodology exists for testing dental composite strength, the minimal strengths identified in the standard for various clinical uses do not represent a value determined from engineering design models or extensive clinical testing [3]. Therefore, the mechanical properties of commercial dental composites vary widely, and the consensus when formulating or developing a new product has been "higher is better." Regardless, the importance of understanding and fully characterizing the fracture and deformation resistance of dental composites cannot be overstated, and many methods exist for this purpose [4]. These methods have been adopted from test methods developed for other materials since composites are a relatively "new" dental material. Therefore, the test methods for dental composites have often been adapted to accommodate the unique specimen manipulation and formation needs for a material that is designed to be placed in situ in one state and then converted to its permanent, mechanically more stable state [5]. A review and evaluation of many of these test methods follow in an attempt to guide investigators endeavoring to study the mechanical properties of dental composites. These test methods have been listed (Table 1) in a way that provides a ranking of the priority of the specific property being tested, as well as the ranking of the specific test methods for evaluating that property [6]. To create this table, the focus was placed on the tests that are considered to be of the highest priority in terms of being the most useful, applicable, and supported by the literature. Others are mentioned briefly to be inclusive [7]. In all cases, when a standard test method exists, including those used in other fields, these have been identified at the beginning of each section. Also, some examples from the composite literature are included for each test method. It is also important to point out that because dental composite materials must be molded into the required test shape and polymerized, the quality of the specimen can influence the outcome of the test [8]. It is probably best to ensure that the material is adequately and uniformly cured for the appropriate amount of time for self-cure materials and with sufficient light energy for photo-cured or dual-cured materials. While these conditions may not always be the most clinically relevant, i.e., they do not test for the effects of under-curing, they will provide the most valid test results and will characterize the optimum properties attainable for that material".

2. Methods

Following properties and respective methods are listed which are necessary to consider developing a dental resin composite:

Strength: Strength is not an innate virtue of any material; it can be varied according to the geometry and fabrication and the testing method of material. The strength of the material is the ability to withstand an applied load without failure or plastic deformation. Force creates internal stress in a body

which is the cause of fracture and strength is resistant to this catastrophic fracture so all types of loading in the oral cavity must be measured in form of strength. The oral cavity material not only faces axial load due to the 3D nature of jaw mechanics. Besides, the strength of the material is a function not only of its composition but also of its quality of preparation, i.e., internal porosity, inclusions, surface flaws, etc.

Fracture toughness: Fracture toughness differs from strength, in that it is an inherent property of a material, and therefore its value should be independent of testing modality or specimen geometry. Fracture toughness is a measure of a material's resistance to the propagation of a crack from a preexisting flaw of known size and infinite sharpness, i.e., a pre-crack.

Fatigue: In materials science, fatigue is the weakening of a material caused by cyclic loading that result in progressive and localized structural damage and the growth of cracks. 2.4. Hardness: Hardness, the resistance of a mineral to scratching, is described relative to a standard such as the Mohs hardness scale. Hardness is an important diagnostic property in mineral identification.

Elastic Modulus: An elastic modulus, or modulus of elasticity, is defined as an object or substance's resistance to being deformed elastically (i.e., non-permanently) when a force is applied to it.

Wear Resistance: Wear is the damaging, gradual removal or deformation of material on solid surfaces. Causes of wear can be mechanical (e.g., erosion) or chemical (e.g., corrosion).

Table 1. Mechanical properties and Tests for Dental Restorative Composites[9].

S.No.	Properties	Types	Test
1	Strength	Flexure	Test Transverse Bending (ISO 4049, ASTM D790-10, ISO178-2010)
			Biaxial flexure (ASTM F394-78)
		Compression(ASTM D695; ISO 604)	Compression (ASTM D695; ISO 604)
		Tension (ASTM D638-14; ISO 527-2)	Uniaxial tensile testing
			Diametral tensile testing (ANSI/ADA Specification #27)
		Impact (ASTM D256-10; ISO 179-1-2010)	Impact (ASTM D256-10; ISO 179-1-2010)
		Shear (ASTM D732-10)	Shear (ASTM D732-10)
2	Toughness	Fracture toughness	Single-edge notch—3-point bending (SENB) (ASTM D5045-14; ISO/NP 13586)
			Compact tension (ASTM D504-14; ISO/NP 13586)
			Double torsion (ASTM C1421-10 for ceramics)
			Chevron notch (ASTM E1304-97)
			Indentation
3	Fatigue	Fatigue strength	Fatigue resistance/limit (ASTM D7791-12: ASTM D7774-12)
			Fatigue strength—staircase method
			Vickers hardness ISO/CD6507-1

4	Hardness	Indentation Hardness	Knoop hardness (ISO 4545-1)
			Rockwell hardness (ISO2039-2)
			Brinell hardness (ISO 6506-1:200)
		Instrumented indentation (ISO/FDIS 14577-ASTM E2546-07)	Indentation hardness, HIT
			Martens Hardness, HM
5	Elastic Modulus	Elastic Modulus	Tensile
			Flexure (ISO 4049; NIST No. 4877)
			Other Test (BFS-piston-on-three-ball; -ball-on-ring or -ring-on-ring, ASTM F394-78 or diametral compression (Brazilian disk test)
		Indentation modulus (ISO/FDIS 14577-1, ASTM E2546-07)	Static
			Dynamic
6	Wear Resistance	Wear—abrasion/three body	OHSU abrasion (ISO TS No. 14569-2)
			Alabama generalized (ISO TS No. 14569-2)
			ACTA (ISO TS No. 14569-2)
		Wear—attrition/contact/two body	OHSU attrition (ISO TS No. 14569-2)
			2.6.2.2 Alabama localized (ISO TS No. 14569-2)
			2.6.2.3 Ivoclar-Willytec simulator
			2.6.2.4 Munich-Willytec simulator
		Wear—toothbrush	Toothbrush/toothpaste (ISO TS No. 14569-2)

2.1 Effect of various fillers and Base Monomer on Mechanical Properties

Hua Wang et al [10] investigated the effect of the two modified fillers m-diatomite and mOX-50 (mass ratios 0:60, 13:52, 21:49, 28:42, 35:35, 49:21, and 37.5:37.5) with base monomer on the mechanical properties of DRC's. the result revealed that properties increased with a mass content of m-diatomite flexural strength were the lowest at 60%–0:60, 105 MPa, and were gradually enhanced by filling with m-diatomite 115,130 and constant 120 MPa respectively. but the elastic modulus, microhardness and compressive strength of the three composites slightly reduced with an increase of m-diatomite content ,5.9,6.9,7.3,6.2,6,5.9,6.1 GPa and 98,122,121,112,110,102,140 HV,148,160,190,162,159,159,160 MPa respectively for above modifies fillers mass ratio.

Anoj Meena et al. [11] fabricated a DRCs with f nano alumina (5–20 wt.%) and marble dust powder (5–20 wt.%) in the base monomer system and the result revealed that water sorption increased with the increase in filler weight percentage which was due to increase in void content in the dental composite. (0–20 wt%) of nano, alumina filler particles were observed to be 1.04, 1.25, 1.36, 1.70, and 2.01%, respectively for the same wt% of marble dust filler particles were observed to be 1.04, 1.41, 1.72, 1.96, and 2.15%, respectively. 5 wt% of nano alumina increased the hardness and compressive strength by 88.46% and 23.25% whereas the addition of 5 wt% of marble powder increased the hardness and compressive strength by 51.27% and 21.2%, respectively.

Sideridou et al. [12] studied the effect of 3-methacryloxypropyl-trimethoxysilane (-MPS) coupling agent on mechanical properties composed by. Silica nanoparticles (Aerosil OX 50) (salinized with 5 -MPS 1.0, 2.5, 5.0, 7.5, and 10 wt.% relative to silica) and Bis-GMA/TEGDMA (50/50 wt./wt.) matrix. the result

revealed that maximum flexural strength of 100 MPa occurred at 2.5 wt.% gamma mps used and maximum flexural modulus for 7.5 wt.% 5.63 GPa and no significant difference of γ mps for FM dynamic elastic modulus E was 6.69 GPa, dynamic viscous modulus E(GPa) was 0.42 for 5 wt.% and highest amount of -MPS (4.57 wt.%) showed the lowest value for tan = 51.3.

Luc D. Randolph et al [13] investigated the relationship between the effect of 17-micron particle (> or < 500 nm) filler characteristics (size, content, geometry, composition) on mechanical properties of dental resin composites, fillers content, and silane evaluation like density, total inorganic wt.% done by thermogravimetric analysis and sedimentation method. The physical and mechanical properties of RBCs are shown table. The study concluded that filler content is proportional to the highest properties and inverse proportional to solvent sorption. The average size for micron-sized fillers was almost always higher than 1m. Ranges for mechanical properties were: 3.7 <Eflexwater< 16.3 GPa, 86 <σflexwater< 161 MPa and 23.7 <hardnesswater<108.3HV0.2/30. Values generally decreased after storage in ethanol/water (Δmax = 86%). High inorganic filler contents (>75 wt%) were associated with the highest mechanical properties (Eflex and σflex> 12 GPa and 130 MPa, respectively) and lowest solvent sorption (~0.3%).

Mitchell et al.[14] experimented effect on fracture toughness of 3 luting cement conventional glass ionomer cement, resin-modified glass ionomer, resin composite cement, and method of mixing (hand and mechanical), and the result revealed that the Mean fracture toughness (MN/m3/2) of CGIC, RMGIC, RCC were KetacCem (hand-mixed) 0.27(MN/m3/2), Fuji I (hand-mixed) 0.34(MN/m3/2), KetacCemMaxicap (capsulate) 0.37(MN/m3/2), Fuji Cap I (capsulated) 0.37(MN/m3/2), Vitremer Luting Cement (resin-modified glass–ionomer cement) 1.08(MN/m3/2), Scotchbond Resin Cement 1.30(MN/m3/2) i.e. The fracture toughness of the resin-modified glass–ionomer cement (Vitremer Luting Cement) was significantly higher than any of the four conventional glass–ionomer cement (KetacCem, KetacCemMaxicap, Fuji I and Fuji Cap I) and the resin composite cement (Scotchbond Resin Cement) was significantly higher than that of the resin-modified glass–ionomer cement.

Liu et al. [15] investigated the effect of reinforcing agent urchin-like hydroxyapatite (UHA) on silica and non-silica composite's mechanical properties composed with BisGMA/TEGDMA based monomer and the result revealed that silanized UHA increase the mechanical properties. The values of SF, EY, SC, Hm, and DTS of the unfilled resin were (93.2 ± 4.6) MPa, (2.8 ± 0.1) GPa, (326.9 ± 11.6) MPa, (17.4 ± 0.7) HV, and (30.3 ± 2.2) MPa, respectively. For the dental resin filled with 10 wt.% UHA, the values of SF, SC, and DTS were (123.5 ± 1.8) MPa, (363.5 ± 14.9) MPa, and (42.7 ± 1.7) MPa, respectively. Thus, SF was improved by 32.5%, SC was improved by 11.2%, and DTS was improved by 40.8%. For the composite with 20 wt.% UHA, the values of SF, SC, and DTS were increased to (118.0 ± 2.9) MPa, (388.7 ± 8.4) MPa, and (46.2 ± 3.5) MPa; and the improvements were 26.6%, 18.9%, and 52.2%, respectively.

Liu et al. [16] studied the effect of porous particles of glass-ceramic fillers (with calcium mica and fluorapatite ratio 80:20 A2 and 50:50 A5) on the bending strength of DRCs. the result revealed that the bending strength of the dental resin composites increases with the content of filler for dense A5 particles. After being filled with porous A5 particles, the bending strength of the dental resin composites drops significantly. The maximum bending strength was A2 porous fillers 75.50±2.40 MPa and minimum A5 dense fillers 59.03±4.47 MPa.

Karabela et al. [17] synthesized the light cure DRCs with silanized nano-silica of 40,20,16,14,7 nm and find the effect of particle size on the mechanical properties of DRCs. the result revealed that flexural strength increases with a decrease in the filler size because stress concentration decreases due to an increase in the surface energy at the interphase of fillers/matrix and lower size increases the surface area of fillers. Flexural Strength and Flexural Modulus of OX50-MPS (40 nm), 90-MPS (20 nm), 130-

MPS (16 nm), 150-MPS (14 nm), 300-MPS (7 nm) were 90, 95, 100, 103, 92 MPa and 5.37, 5.24, 5.49, 5.43, 4.45 GPa respectively.

Alsharif et al. [18] experimented on filler loading (wt.%) of 4.6 μm Al3O3 on the mechanical properties of DRCs. Vickers hardness test value (HV), Flexural modulus increase with filler loading but Flexural strength decrease with the increase of filler loading due to an increase of adequate shape, and fillers do not hinder crack propagation. Hardness (HV), FM(GPa), FS(MPa) of 0,40,50,60 wt.% was 14.4,18.6,22.2,23.5 HV, 1.5,3.7,4.7,5.7 GPa and 84.5,83.2,77.1,74. MPa.

Rodríguez et al. [19] studied the effect of silanized (SiNPMPS) (80 nm), (SDSiNPMPS) (3.5 μm), (BaAlBoSiMPS) (1.0 μm) organic fillers in DRCs mechanical properties. Results revealed that flexural strength decreases at higher filler loading due to higher stress concentration in particle in the resin composite was counteracted by increasing mechanical failure between resin matrix and fillers inorganic, at 60 wt.% filler content flexural strength of silanized (SiNPMPS), (SDSiNPMPS), (BaAlBoSiMPS) were 25,60,72 MPa respectively. Up to intermediate filler content 40 wt. % compressive strength increase but later CS of (SiNPMPS) decrease with filler content all three composites had CS 125 MPa at a filler loading of 20 wt.%. SDSiNPMPS and BaAlBoSiMPS composites maintained a steady increase in the compression strength, achieving a value close to 250 MPa for both systems at 72 wt.%.

Kumar et al.[20] develop new dental material with Gypsum and Bis-GMA, TEGDMA, CQ, and EDMAB as an organic filler and base matrix, and Simultaneous Thermal Analysis (STA) result revealed that 2 wt.% gypsum filled dental composite exhibited maximum thermal stability and the highest value of storage modulus composites with the highest filler loading exhibited the highest depth of cure (3.9 mm) and lowest polymerization shrinkage (2.02%). According to ISO 4049-2009 standard, the depth of cure value should not be less than 2 mm. In this study, the depth of cure of unfilled composite particles was found to be 2.7 mm.

Chadda et al. [21] investigated the Mechanistic interpretations of fracture toughness and correlations to wear behavior of hydroxyapatite and silica/hydroxyapatite filled bis GMA/TEGDMA micro/hybrid dental restorative composites. The micro-hybrid (silica/hydroxyapatite combination-based) composites showed relatively lower fracture toughness than micro-filled (hydroxyapatite-only-based) composites. the experiment showed wear rate of the specimens in the ascending order of H30<H40<H20<H0<SH30<SH20<SH0<SH50. The unfilled composites had a hardness value of ~161 MPa whereas the hardness of dental composites with 50 wt% of hydroxyapatites reached ~416 MPa

Mohammed. et al [22] develop PMMA resin-based DRCs with fly ash, fly dust, zirconia, and aluminum (1%, 2%, and 3%), and the result revealed that flexural strength, Maximum Shear stress, flexural modulus, impact strength, and fracture toughness increased with the addition of nanopowders (fly ash, fly dust, zirconia, and aluminum), maximum values of flexural strength and Maximum shear stress reach to 101Mpa and 2.4738Mpa respectively for (PMMA: 2% n F.D) Nano composite.

Tian et al. [23] studied the compare mechanical properties of DRCs of Bis-GMA/TEGDMA dental resins (without conventional glass filler) and composites (with conventional glass filler) with various mass fractions of nano fibrillar silicate (FS). The result revealed that (1% and 2.5%) of nano FS into BisGMA/TEGDMA (50/50 mass ratio) dental resins/composites improved the mechanical properties substantially. A larger mass fraction of impregnation (7.5%), however, did not further improve the mechanical properties (one-way ANOVA, $P > 0.05$) and may even reduce the mechanical properties.

Kumar et al. [24] formulated a silane treated marble dust-filled (0-9 wt.%) dental composite. Results revealed that Vickers hardness values of the dental composite filled with 0, 3, 6, and 9 wt.% of silane-treated marble dust content were 69HV, 72HV, 84HV, and 96HV, respectively. that unfilled composite exhibited compressive strength of 175 MPa but the compressive strength of dental composites filled

with 3 wt.%, 6 wt.%, and 9 wt.% of silane-treated marble dust was 210, 245, and 296 MPa. unfilled composite exhibited a flexural strength of 55 MPa. The flexural strength of dental composite filled with 3 wt.%, 6 wt.%, and 9 wt.% of silane-treated marble dust was 62.5MPa, 75 MPa, and 80 MPa, respectively.

Wang et al [25] investigated the effect of the two modified fillers m-diatomite and mOX-50 (mass ratios 0:60, 13:52, 21:49, 28:42, 35:35, 49:21, and 37.5:37.5) with base monomer on the physical and chemical properties of DRC's. the result revealed that the majority of the diatomite morphologies were of a sieve plate, and the remaining were of the cylinder. Chemical compositions of the raw diatomite and acid-leached diatomite (wt.%) were Na2O, MgO, Al2O3, SiO2, SO3, K2O, TiO2, Fe2O3, others which were in Raw materials (wt.%) 0.24 0.76 15.00 75.60 0.14 1.90 0.74 5.00 0.62 and Acid-leached diatomite 0.20 0.05 2.60 95.45 0.10 1.10 0.26 0.11 0.13 respectively. Impurity content decreased in treated diatomite except for silica. Corresponding specific surface area SBET (m2/g), pore-volume V (cm3/g), and pore diameter D (nm) for raw diatomite and acid-leached diatomite were 54.75 0.12 3.70 and 42.66 0.24 16.30 respectively. The specific surface area of the acid-leached diatomite was lower compared to the raw materials. The spectra reveal that the raw diatomite before purification had a high absorbance 1 After leaching, the absorbance was .7 after sintering at 500 °C for 3 h lowest level of absorbance was .2 in the UV–visible light region Thus, the results of the UV–vis diffuse reflection spectra coincide with the chemical compositions from the X-ray fluorescence.

Meena et al. [26] investigated a comparison between nanohydroxyapatite (HA) (5–20 wt.%) and mineral trioxide aggregate (MTA) (5–20 wt.%) on the physical, mechanical, and thermomechanical properties. Result revealed water sorption was improved with the addition of nanohydroxyapatite and mineral trioxide aggregate it were 1.05%, 1.58%, 2.15%, 2.85% and 3.5% and 1.05%, 1.24%, 1.69%, 1.76% and 1.96% respectively. It was also revealed that the hardness of filled dental composite was significantly higher than the hardness of unfilled dental composite (78 Hv). Hardness was 78,88,112, 132,150 & 156,219,243,292, for DCH-0, DCH-5, DCH-10, DCH-15, DCH-20 &DCMT-5, DCMT-10, DCMT-15, DCMT-20 respectively. The incorporation of 5 wt.% of HA & MTA increased 62.35% & 5.44%.

Chen et al. [27] investigate the effect of the reinforcement of Bis-GMA/TEGDMA dental resins (without conventional glass filler) and the corresponding composites (with conventional glass filler) containing varied mass fractions of halloysite nanotubes (HNTs). The result revealed that Impregnation of small mass fractions (e.g., 1% and 2.5%) of the silanized HNTs in Bis-GMA/TEGDMA dental resins/composites improved mechanical properties significantly; however; large mass fractions (e.g., 5%) of impregnation did not further improve the mechanical properties. Result in two opposite effects: the reinforcing effect due to the highly separated and uniformly distributed HNTs, and the weakening effect due to the formation of HNT agglomerates/particles.

Aydinoğlu et al. [28] studied the effect of the silica fillers were obtained from colloidal silica solution on the mechanical, chemical, and physical properties of dental composites, and the result revealed that FS of the C-Si composite system, unsilanized fillers were used, was 71.1MPa, FS of the C-Silan dental composite systems was 112 MPa and CS 148.5 MPa, AFS 45.1 MPa and E 6.6 GPa in C-Si composite structure in which unsilanized fillers were used. On the other hand, these values were as follows CS 184.1 MPa, AFS 45.1 MPa, and E 10.4 GPa in C-Silane .

3. Results

The present study on the mechanical Properties of Dental resin composites had derived the following significant results and conclusions.

(1) The reinforcement of fillers' contents according to the size, shape, and wt.% increases the physical, mechanical, and tribological properties of DRCs.

(2) The international standardization of evaluation criteria is mandatory according to the recommendations.

(3) It is further revealed that the mechanical properties of the dental composite were improved by adding filler as well as by providing silane treatment to filler to increase the adhesion properties between resin and filler.

(4) The properties for evaluating resin composites were ranked in the priority of measurement as follows:

4. Discussion

The high degree of conversion and steady delivery of filler reinforcement in the base resins, bacteria degradation, and polymerization shrinkage is a challenge in DRCs, and a good design of the experiment (multi-criteria design techniques) of all factors play a significant role in the result.

In adaption with the evolution of more cultivated monomers and resin fillers, the age of contemporary dental restorative is in needs to increase, and only by using a renovated combination of all these receivable techniques will one be capable to obtain an openly best dental RBC.

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