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Nanofilled Resin Composite Properties and Clinical Performance: A Review

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Clinical Relevance

Nanocomposites have been found to exhibit properties and clinical performance comparable to those of several hybrid composites but better than microfilled composites. However, there is no long-term evidence yet to show a superior performance that justifies their use in stress-bearing areas.

SUMMARY

The aim of this review was to compile recent evidence related to nanofilled resin composite materials regarding the properties and clinical performance. Special attention was given to mechanical properties, such as strength, hardness, abrasive wear, water sorption, and solubility. The clinical performance of nanocomposite materials compared with hybrid resin composites was also addressed in terms of retention and success rates, marginal adaptation, color match, and surface roughness. A search of English peer-reviewed dental literature (2003-2017) from PubMed and MEDLINE databases was conducted using the terms "nanocomposites" or "nanofilled resin composite" and "clinical evaluation." The list was screened, and 82 papers that were relevant to the objectives of this work were included in the review. Mechanical properties of nanocomposites are generally comparable to those of hybrid composites but higher than microfilled composites. Nanocomposites presented lower abrasive wear than hybrids but higher sorption values. Their clinical performance was comparable to that of hybrid composites.

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INTRODUCTION

Resin composite materials are increasingly used in modern dentistry due to several desirable qualities, such as esthetic appearance and good physical and mechanical properties.[1] The availability of numerous commercial products makes resin composite suitable for use in several clinical applications, including as restorative materials, cavity liners, core buildups, and luting cements, to name a few.[2-4] Previous research has addressed several shortcomings of composites, such as polymerization shrink-

age, strength, and wear resistance.[5-9] A wide range of resin composites is available for anterior and posterior restorations. This implies a wide range of organic and inorganic constituents that will influence their clinical handling and performance.[1] The main composition of resin composites consists of an organic polymeric matrix, inorganic fillers, and a silane coupling agent that links the first two components together.[10] Mechanical properties and esthetic appearance of resin composites have been shown to be influenced by their composition and microstructure.[11,12] Despite the improvements in various properties over recent years, major changes to their composition have involved mainly the fillers rather than the monomer systems, which were originally developed by Bowen[13] in 1962.

The original resin matrix monomer system was based on the formula presented by Foster and Walker[14] consisting mainly of (Bis-GMA: 2,2-bis[4-(2-hydroxy-3-methacryloxypropoxy) phenyl] propane) and later urethane dimethacrylate. Several approaches were suggested to modify the monomer component to create resin composites with no or minimal shrinkage on polymerization and improved wear resistance. One of the modifications in the monomer system was the use of ring opening monomers. These monomers resulted in the development of resin composites with decreased polymerization shrinkage (ie, silorane-based resin composites).[15] Organically modified ceramics (ormocers) were introduced to overcome problems of polymerization shrinkage associated with conventional methacrylate-based resin composites. Ormocers contain inorganic-organic copolymers in addition to inorganic filler particles.[16] Ormocers have shown lower wear rates compared to other composites[17] and similar shrinkage to hybrid composites despite their lower filler content.[18]

It is well documented that mechanical properties of resin composites are significantly influenced by the filler particle morphology (shape), size range, and volume content.[11,19,20] The increasing demand for esthetic dentistry has led to the development of resin composites used for direct restorations. These composites have demonstrated improved clinical performance both physically and esthetically.[21] Traditional composites have been classified based on filler size. The classification divided the composites into macrofilled, microfilled, hybrid, and microhybrid materials. The introduction of nanometer-sized particles has been one of the latest developments in the field and is thought to offer superior esthetics and polishability in addition to excellent wear resistance and strength.[21,22]

In his review of resin composites, Ferracane[2] described the chronological development of resin composites outlining their classification according to the filler particle size as follows: macrofill (10 to 50 μm), microfill (40 to 50 nm), and hybrid (10 to 50 μm+40 nm). Hybrid composites were further distinguished as "midifill resin composites" with an average particle size slightly greater than 1 μm and a portion of the 40 nm fillers. Further refinement of the filler particles resulted in what is known as microhybrids (0.6 to 1 μm and 40 nm). Finally, nanofilled resin composites (1 to 100 nm) and nanohybrid that is a combination of microhybrid and nanofilled-size particles were introduced.

The growing interest in nanotechnology and its use in resin composites was based on the desire to utilize the ability of nanosized particles to alter the structure of the composite. This in turn may improve mechanical, chemical, and optical properties and develop a resin composite that can perform optimally in all parts of the mouth.[22,23] Consequently, Mitra and others[22] introduced novel nanofillers and then utilized various methacrylate resins and curing technologies to develop nanocomposites. This nanocomposite was subsequently marketed as the Filtek range of restorative materials (3M ESPE, St Paul, MN, USA).

Two classes of resin composites that include nanoscale filler particles in their composition have been introduced, namely, nanofilled and nanohybrid resin composites. While nanofilled composites use nanosized particles throughout the resin matrix,[22] nanohybrids include a mixture of nanosized and conventional filler particles.[24] It has been previously suggested that the size of the fillers observed for the nanohybrid composites could be a reason to not refer to them as nanostructured materials. This suggestion was based on the fact that microhybrid composites may contain a mixture of similar nanosized particles in combination with larger filler particles.[1] Nanosized fillers can be categorized as either isolated discrete particles, with dimensions of around 5 to 100 nm, or fused aggregates of primary nanoparticles, where the cluster size may exceed 100 nm.[25] It has been proposed that finer particles when incorporated into resin composite will lead to less interparticle space, which will provide more protection to the more vulnerable, softer resin matrix. This in turn will result in reduced "plucking" of filler particles from the material surface.[26,27]

Previous research has focused on testing various properties of resin composites to evaluate their performance in both laboratory and clinical studies. A large number of these studies aimed at comparing nanocomposites with hybrid and microfilled resin composites.[28] Therefore, the objective of the present work was to review laboratory studies that were undertaken on the so-called nanocomposites to examine strength, fracture toughness, surface hardness, abrasive wear, water sorption, and solubility. In addition, a review of the clinical performance of dental nanocomposites was undertaken. Three major categories of resin composites, namely, nanocomposites, hybrid, and microfilled composites, were compared for the sake of offering a clear distinction between their performance and properties. A search of English peer-reviewed literature (2003-2017) from PubMed and MEDLINE databases was conducted using the terms "nanocomposites" or "nanofilled resin composite" and "clinical evaluation." The list was screened, and 82 papers that were relevant to the objectives of this work were included.

STRENGTH

The main aim of incorporating nanofillers into resin composites (ie, nanocomposites) is to create materials that can be used to restore both anterior and posterior teeth with a high initial polish and gloss. In addition, they should exhibit mechanical strength suitable for use in high-stress-bearing areas.[22] Table 1 summarizes the main resin composites mentioned in this literature with their reported classification according to average filler size and the manufacturer.

Flexural Strength

One of the most commonly tested mechanical properties of dental restorative materials is flexural strength (FS), which is considered important for characterizing brittle materials. This type of test generates complex stresses that combine tensile, compressive, and shear stresses when specimens are loaded.[29] Several studies examined FS of a number of commercial nanocomposites comparing hybrid and microfilled composites.[11,13,22,28-36] Direct comparison showed that the FS of nanocomposites was equivalent to or even higher than other composites tested[11,13,22,29,31,37] with values ranging from 103 to 192 MPa.[38-40] Mitra and others,[22] who developed nanocomposite materials in 2003, reported FS values ranging from 153 to 177 MPa. These values were significantly higher than a number of tested hybrid composites, comparable to that of one hybrid material and significantly higher than the microfilled composite (Table 2). Similarly, Pontes and others[29] reported significantly higher FS of a nanocomposite compared with a hybrid. On the other hand, several investigators reported FS values of several nanocomposites comparable to or significantly lower than a number of hybrid materials but significantly higher than microfilled composites.[11,31,36,40-42]

A number of studies examined the influence of several factors, such as light polymerization mode, filler content (weight), and degree of conversion (DC) (defined as the percentage of reacted aliphatic C=C bonds from the dimethacrylate monomers present in their polymeric matrices),[43] on the FS of nanocomposites. Da Silva and others[41] examined the influence of using three different polymerization modes on the FS of a hybrid and a nanocomposite (Table 2). The results showed that the FS of the tested composites was not influenced by varying the light polymerization mode. Furthermore, FS of the hybrid composite was significantly higher than the nanocomposite tested. Similar conclusions were drawn by Pontes and others,[29] who reported no significant effect on FS of a nanocomposite when varying polymerization modes. Similarly, Beun and others[31] and Rodrigues and others[42] reported no significant influence of varying polymerization modes on FS of nanocomposites and hybrid composites tested. Degree of conversion has been shown to influence mechanical properties of resin composites.[44] Beun and others[31] showed a lower DC when using an LED curing unit for a 10 seconds of curing time compared with a QTH curing unit at a 2-mm depth. The 2-mm thickness is traditionally used and recommended by the ISO standard (4049) for dental resins.[45] However, in their study, Beun and others[31] reported that FS was not a discriminating factor used to differentiate the tested composites since the nanocomposites showed comparable FS values to the universal hybrids. Similar conclusions were drawn by Rodrigues and others[42] regarding the effect of DC on FS. They reported comparable FS values of composites tested that were attributed to the high filler loading of both composites (Table 2).

The influence of filler content on FS of nanocomposites has also been examined comprehensively.[11,29,31,40,46,47] Rodrigues Junior and others[11] showed that there was a positive correlation between the filler weight (FW) and FS of a nanocomposite (FW 84%). The nanocomposite showed intermediate strength values compared to other hybrid composites (FW 74% to 80%) and microfilled

Table 1: *Summary of Resin Composites Reviewed, Category, and Manufacturer Information*

Resin Composite	Classification	Manufacturer
Filtek Supreme	Nanocomposite	3M ESPE, St Paul, MN, USA
Filtek supreme Z350	Nanocomposite	3M ESPE
Filtek Ultimate	Nanocomposite	3M ESPE
Filtek Supreme Plus	Nanocomposite	3M ESPE
Grandio	Nanocomposite	Voco, Cuxhaven, Germany
Grandio Flow	Nanocomposite	Voco
Esthet X improved	Nanocomposite	Dentsply Caulk, Milford, DE, USA
Premise	Nanocomposite	Kerr, Orange, CA, USA
TPH[3]	Nanocomposite	Dentsply Caulk
Concept Advance	Nanocomposite	Vigodent, Rio de Janeiro, Brazil
Ceram X	Nanocomposite	Dentsply Caulk
Tetric EvoCeram	Nanocomposite	Ivoclar Vivadent, Amherst, NY, USA
Venus Diamond	Nanocomposite	Heraeus Kulzer, GmbH, Hanau, Germany
Charisma Diamond	Nanocomposite	Heraeus Kulzer
Ceram X mono	Nanocomposite	Dentsply Caulk
Ceram X Due	Nanocomposite	Dentsply Caulk
Clearfil Majesty	Nanocomposite	Kuraray America Inc, Houston, TX, USA
Ice	Nanocomposite	SDI, Bayswater, Australia
Filtek Z250	Hybrid	3M ESPE
Filtek P60	Hybrid	3M ESPE
Esthet X	Hybrid	Dentsply Caulk
Point 4	Hybrid	Kerr
Charisma	Hybrid	Heraeus Kulzer
Clearfil AP-X	Hybrid	Kuraray America
Amaris	Hybrid	Voco, Cuxhaven
TPH Spectrum	Hybrid	Dentsply Caulk
Venus	Hybrid	Heraeus Kulzer
Filtek Z100	Hybrid	3M ESPE
Tetric Ceram	Hybrid	Ivoclar Vivadent
Prime-Dent	Hybrid	Prime Dental Manufacturing, Chicago, USA
Heliomolar	Microfilled	Ivoclar Vivadent
Helio Fill	Microfilled	Vigodent
Filtek A110	Microfilled	3M ESPE
Durafil	Microfilled	Heraeus Kulzer
Surefil	Packable/hybrid	Dentsply Caulk
Filtek Silorane	Silorane resin	3M ESPE Dental Products, St. Paul, MN, USA

composite (FW 64%). However, it has been reported that the fracture behavior and the structural reliability seem to not be affected in highly filled composites compared with composites with lower filler content, such as microfilled resin composites.[42] This is because the volume percent content of the fillers may not be markedly different. A number of investigators indicated that filler content and material category had a significant influence on mechanical properties of resin composites, including nanocomposites.[28,39,47-49] Higher strength was associated with spherical filler particles,[47] and the highest values of FS were observed at a filler volume of 60%. Lin and others[38] also suggested higher FS values being associated with higher filler content when testing FS of several nanocomposites; however, in their study, spherical filler particles were not associated with higher strength values. Contrary to the results reported by Lin and others,[38] Pontes and others[29] reported no positive correlation between filler content and FS, which could be related to the fact that different products where examined in the two previously mentioned studies. Lawson and Burgess[46] attempted to evaluate the

influence of nanofiller weight percent on mechanical properties of experimental resin composites. Three experimental nanocomposites were formulated with different weight percent filler loads (25%, 50%, and 65%). There was an increase in the FS of all experimental composites up to 50% weight content of the fillers.

Ilie and Hickel[28] reported that large variations exist between resin composites within the same category. Flexural strength values ranging from 82 to 125 MPa were reported among 72 commercial composites tested (nanocomposites, hybrid, packable, microfilled, and flowable composites). Comparable mechanical properties were found among a number of hybrid and nanocomposites that were expectantly higher than the flowable composites that have a lesser amount of fillers.[28]

In conclusion, it would be difficult to predict the performance of a single material based on its type. It is reasonable to conclude that the reported FS of nanocomposites was not superior to that of most hybrid composites but was significantly higher than microfilled composites. Furthermore, it should be noted here that the previously mentioned studies used filler weight percent rather than filler volume percent when comparing different composites. It has been mentioned previously that percent filler content is perhaps best expressed in terms of volume because the mechanical properties of resin composites are dictated mainly by their filler volume fraction.[16]

Compressive and Diametral Tensile Strength

Compressive strength (CS) and diametral tensile strength (DTS) have been positively correlated in the literature when routinely testing mechanical properties of restorative materials. In both tests, the samples are subjected to a compressive load along different planes. Subsequently, fractures occur due to a combination of tensile and shear stresses.[50,51] Mitra and others[22] reported CS and DTS values of nanocomposites to be comparable to or higher than the tested hybrid and microfilled composites. The CS and DTS of nanocomposites have also been studied by several investigators who reported variability among nanocomposites when compared with other composites.[1,13,21,22,29,33,40] Several investigators attributed variability and differences in part to the nanofiller content (wt%).[21,40]

The study by Lu and others[13] showed comparable values of CS and DTS of a number of nanocomposites and hybrid composites. Similar trends were observed by de Moraes and others,[1] Pontes and others,[29] and Lien and Vandewalle.[36] This was attributed to the presence of large individual filler particles in all of them (Table 3).[1]

The CS and DTS of a number of nanocomposites were evaluated compared with hybrid, microfilled, flowable, and ormocer-based composites.[28] Large variations were observed in the strength values (CS: 103 to 267 MPa; DTS: 32 to 45 MPa). Nanocomposites displayed the highest DTS values and comparable CS values to hybrid composites. It was previously reported that the strongest influence was for the filler volume on the DTS and that the influence of material category was low and influenced mainly the CS.[29,52,53] Generally, DTS of nanocomposites is at least as good as that of several hybrid composites and higher than a number of hybrid and packable composites. However, Ilie and Hickel[28] reported that having a lower modulus of elasticity makes nanocomposites experience more elastic deformation under functional stresses. Therefore, their clinical success is questionable when used in stress-bearing areas.

Fracture Toughness

Fracture toughness (FT) has been occasionally assessed for nanocomposites in addition to the previously mentioned properties.[22,33,36,54,55] FT is used for assessing brittle materials in order to identify a material's resistance to fracture. It is also used to assess the amount of energy that is needed to cause the propagation of a crack from a well-defined preexisting crack or notch placed in the tested material.[54] However, due to the sensitivity of the test to the dimensions of the prepared notch or flaw, the results can vary among studies.[54] Mitra and others[22] developed nanocomposites and compared the seven-day FT with hybrid and microfilled composites. The reported values of the two nanocomposites (standard and translucent) were 1.3 and 1.2 MPa$\sqrt{m}$, respectively, comparable to the hybrid (1.2 MPa$\sqrt{m}$) and significantly higher than the microfilled (0.9 MPa$\sqrt{m}$). However, FT of the translucent nanocomposite was significantly lower than other hybrids tested (1.4 MPa$\sqrt{m}$) (Table 4). Similarly Ilie and others[54] reported that FT of a nanocomposite (1.46 MPa$\sqrt{m}$) was significantly higher than microfilled and flowable composites but lower than most hybrid composites. A number of researchers reported that FT of a nanocomposite was comparable to that of several hybrid composites.[30,33,55] Improved mechanical properties of nanocomposites have been previously attributed to the

Table 2: *Flexural Strength (FS, MPa) of Resin Composites (N, Nanocomposite; H, Hybrid; M, Microfilled)*

Study	Material	Category	FS (MPa)[a]	Test Conditions
Mitra and others[22]	Filtek A110	M	94 E	
	TPH spectrum	H	136 D	Three-point bending test
	Point 4	H	136 D	
	Esthet X	H	140 C	
	Filtek Supreme standard	N	153 BC	
	Filtek Z250	H	161 AB	
	Filtek Supreme translucent	N	177 A	
Pontes and others[29b]	Charisma	H	112, 126, 113 B	Three-point bending test
	Filtek Z350	N	138, 142, 149 A	Curing modes: Conventional QTH (400 mW/cm^2 for 40 s) Conventional LED (900 mW/cm^2 for 20 s_ Ramped LED (5-s exposure, then exposure to 900 mW/cm^2 for 15 s_
Lu and others[13]	Esthet X	H	125 B	Three-point bending test
	Tetric Ceram	H	134 AB	
	Filtek Supreme	N	140 A	
Rosa and others[40]	Grandio	N	103 B	Three-point bending test
	Esthet X	H	106 AB	
	Filtek Z350	N	123 A	
Lien and others[36c]	Esthet X	H	95 C	Three-point bending test
	Filtek Supreme	N	115 AB	
	Filtek Silorane	H	125 AB	
	Filtek Z250	H	137 A	
Rodrigues Junior and others[11]	Helio Fill	M	86 D	Three-point bending test 7-d water storage
	Filtek Supreme	N	119 C	
	Charisma	H	127 C	
	Esthet X	H	145 B	
	Filtek Z250	H	168 A	
Rodrigues Junior and others[42]	Filtek Supreme	N	135 A	Three-point bending test
	Filtek Z250	H	140 A	
Beun and others[31c]	Durafill VS	M	50 B	Three-point bending test Curing modes: Conventional QTH (650 mW/cm^2) LED (450 mW/cm^2 for 10 s)
	Filtek A110	M	70 AB	
	Venus	H	80 AB	
	Grandio flow	N	85 AB	
	Tetric Ceram	H	90 A	
	Grandio	N	110 A	
	Point 4	H	110 A	
	Filtek Supreme	N	115 A	
	Filtek Z100	H	120 A	
da Silva and others[41b]	Filtek Supreme	N	173C, 185 BC, 190 BC	Three-point bending test Curing modes: Standard (650 mW/cm^2 output intensity (30 s) High intensity (1000 mW/cm^2 (20 s) Ramped (100 to 1000 mW/cm^2 for 10 s + 1000 mW/cm^2 for 10)
	Filtek P60	H	225 A, 209 AB, 221 A	

[a] *Means with the same letters within each study are not statistically different. For studies with multiple values, one letter was used to indicate significant difference between different materials.*
[b] *Multiple values for each material property indicate the reported values under each test condition in the study.*
[c] *Approximate values are used since data were reported using a chart presentation.*

Table 3: *Compressive Strength (CS) and Diametral Tensile Strength (DTS, MPa) of Resin Composites (N, Nanocomposite; H, Hybrid; M, Microfilled)*

Study	Material	Category	CS (MPa)[a]	DTS (MPa)	Test Conditions
Mitra and others[22]	Filtek A110	M	376 B	52 D	NA
	TPH Spectrum	H	378 B	80 B	
	Esthet X	H	422 AB	66 C	
	Filtek Supreme standard	N	426 A	80 B	
	Point 4	H	433 A	76 B	
	Filtek Z250	H	454 A	96 A	
	Filtek Supreme Translucent	N	458 A	87 A	
Lien and others[36b]	Filtek Silorane	H	250 C	48 A	NA
	Esthet X	H	320 B	52 A	
	Filtek Supreme	N	360 AB	54 A	
	Filtek Z250	H	390 A	58 A	
Rosa and others[40]	Esthet X	H	173 A	41 B	NA
	Grandio	N	181 A	42 AB	
	Filtek Z350	N	184 A	50 A	
Lu and others[13]	Filtek Supreme	N	262 A	54 A	NA
	Esthet X	H	263 A	46 B	
	Tetric Ceram	H	263 A	49 AB	
de Moraes and others[1]	Concept Advance	N		38 B	NA
	Premise	N		40 B	
	TPH	N		53 AB	
	Filtek Z250	H		53 AB	
	Grandio	N		54 AB	
	Filtek Supreme XT	N		58 A	
Pontes and others[29c]	Charisma	H		50, 50, 50 B	Curing modes: Conventional QTH (400 mW/cm^2 for 40 s) Conventional LED (900 mW/cm^2 for 20 s) Ramped LED (exposure for 5 s, followed by exposure to 900 mW/cm^2 for 15 s)
	Filtek Z350	N		54, 55, 56 A	

Abbreviation: NA, not applicable.
[a] *Means with the same letters within each study for each property are not statistically different.*
[b] *Approximate values are used since data were reported using a chart presentation.*
[c] *Multiple values for each material property indicate the reported value under each test condition in the study.*

incorporation of nanofillers into the resin matrix. This in turn leads to a reduction in interparticle space and therefore protection of the organic matrix. Furthermore, nanofillers can act as points that may slow the initiation of or even stop crack propagation.[54] However, the variations in test protocols and sample preparation among studies may lead to different reported values, making direct comparisons difficult. Generally, the previously mentioned studies indicate that FT of nanocomposites was not superior to that of hybrids but higher than microfilled composites. Further studies using comparable methodology are required to facilitate comparison between materials.

HARDNESS

The hardness of commercial resin composites is a property that is closely related to wear resistance and long-term stability of these materials in the oral environment.[56] Surface hardness has also been used as an indicator for the degree of monomer conversion by using the hardness ratio of the bottom and top surfaces of tested samples.[57] Previous literature suggests that a composite is "properly" polymerized when the maximum hardness of the bottom surface is $\geq$80% of the hardness value of the top surface.[13,21] The hardness of composites has been positively correlated with filler volume %[58] and with filler weight %.[21,29,31,46]

Table 4: *Fracture Toughness (FT, MPa$\sqrt{m}$) of Resin Composites (N, Nanocomposite; H, Hybrid; M, Microfilled)*

Study	Material	Category	FT (MPa$\sqrt{m}$)[a]	Test Conditions
Mitra and others[22]	Filtek A110	M	0.9 C	Chevron-shaped notched short rod method, 7-d storage
	Filtek Supreme Translucent	N	1.2 B	
	Esthet X	H	1.2 B	
	Point 4	H	1.2 B	
	Filtek Supreme standard	N	1.3 AB	
	Filtek Z250	H	1.4 A	
	TPH Spectrum	H	1.4 A	
Lien and others[36b]	Esthet X	H	0.58 A	Single-edge notched beam method, 24-h storage
	Filtek Supreme	N	0.59 A	
	Filtek Z250	H	0.67 A	
	Filtek Silorane	H	0.68 A	
Rodrigues Junior and others[42]	Filtek Supreme	N	1.3 B	Notched bar method, 24-h storage
	Filtek Z250	H	1.5 A	
Hamouda and Abd Elkader[30]	Prime Dent	H	6.28 A	Sharp notch bar method, 24-h storage
	Filtek Supreme	N	6.54 A	
Thomaidis and others[55]	Filtek Ultimate	N	1.20 A	Single-edge notched beam method
	Filtek Z250	H	1.43 A	

[a] *Means with the same letters within each study are not statistically different.*
[b] *Approximate values are used since data were reported using a bar chart.*

Various trends have been reported when microhardness of nanocomposites was compared to other types of resin composites (Table 5). Mota and others[21] reported a wide range of Knoop microhardness values of nanocomposites that were attributed mainly to differences in the filler content (55 to 123 KHN). Beun and others[31] reported significantly higher hardness values of the nanocomposites compared to most of the hybrid and microfilled composites tested in their study. Several researchers reported higher hardness values for a number of nanocomposites compared to hybrid composites. This was attributed to higher filler content, large and densely packed filler particles, and resin content of the nanocomposite tested (Table 5).[1,12,29,59] Similarly Lombardini and others[57], and Poggio and others[60] reported greater surface microhardness of nanocomposites tested compared with the hybrid composites, a finding that was statistically significant (Table 5). The hardness values were not influenced by varying polymerization mode or time or sample thickness, something that was also reported by other researchers.[29,61]

On the other hand, the microhardness of a nanocomposite was found to be inferior to that of a hybrid by several researchers who attributed this to the complex nature of the nanocomposites' filler content, larger filler volume, and greater amount of pigment. These proposed factors may lead to light attenuation yielding a decreased degree of polymerization (Table 5).[36,42,58,62-64] Cao and others[65] reported significantly lower Vickers hardness (VH) values of the nanocomposite compared with all tested hybrid composites in their study. Each composite showed a distinct performance in terms of hardness and wear that was attributed to the formulation of each material. Comparable microhardness values were reported by da Silva and others[41] for a nanocomposite and a hybrid. However, using high-intensity light yielded the highest microhardness values. A positive correlation between curing method, depth of cure, curing time, and the hardness of nanocomposites were also reported by others.[66-68] Similarly, Marchan and others[69] reported better microhardness values of tested nanocomposites when light cured for 20 seconds using QTH and LED units compared to 10 seconds. The majority of the nanocomposites produced better VH when cured by LED compared with QTH, the reason for which was unclear. One nanocomposite showed higher VH compared to the other nanocomposites due to its higher filler content (Table 5).

The different values of microhardness reported indicate the influence of the specific formulation of each material, ultimately affecting its hardness behavior.[40,65] Moreover, different study protocols and testing methods may account for this variability in reported values. Consequently, it would be difficult to accurately compare results. Therefore, further investigations using comparable methodolo-

Table 5: *Hardness Values of Resin Composites (N, Nanocomposite; H, Hybrid; M, Microfilled)*

Study	Material	Category	Hardness[a]		Test Conditions
De Moraes and others[1]	Concept Advance	N	44 E		Knoop hardness
	TPH	N	54 D		
	Premise	N	62 C		
	Filtek Z250	H	69 B		
	Filtek Supreme XT	N	72 B		
	Grandio	N	111 A		
Pontes and others[29]	Charisma	H	40 B		Vickers hardness Curing modes: Conventional QTH (400 mW/cm^2 for 40 s) Conventional LED (900 mW/cm^2 for 20 s) Ramped LED (exposure for 5 s, followed by exposure to 900 mW/cm^2 for 15 s)
	Filtek Z350	N	64 A		
			Top	Bottom	
Poggio and others[60b]	Amaris	H	41, 46, 45	36,39,39 D	Vickers hardness Curing times and modes: Standard: 1000 mW/cm^2 for 20 s Standard: 1000 mW/cm^2 for 40 s Soft start: 0 to 1000 mW/cm^2 for 5 s +1000 mW/cm^2 for 35 s
	Filtek Silorane	H	51, 50, 51	45,45,47 C	
	Esthet X	H	52, 59, 60	45,55,56 C	
	Ceram X Mono	N	55, 62, 61	44,58,58 C	
	Filtek Supreme XT	N	82, 82, 84	79,79,81 B	
	Grandio	N	104, 105, 103	101,100,100 A	
Lombardini and others[57b]	Amaris	H	44, 44	39,36 D	Vickers hardness Depth of cure and curing time: 2 mm and 3 mm for 40 s
	Filtek Silorane	H	51, 51	45,44 C	
	Esthet X	N	55, 52	44,42 C	
	Ceram X Mono	H	57, 57	55,46 C	
	Filtek Supreme XT	N	83, 82	79,75 B	
	Grandio	N	104, 104	101,91 A	
Lien and others[36c]	Esthet X	H	41 C		Knoop hardness
	Filtek Silorane	H	44 C		
	Filtek Supreme	N	57 B		
	Filtek Z250	H	63 A		
Rodrigues Junior and others[42]	Filtek Supreme	N	57	43 B	Knoop hardness
	Filtek Z250	H	62	55 A	
Beun and others[31c]	Durafill VS	M	19 F		Vickers hardness
	Filtek A110	M	38 E		
	Tetric Ceram	H	40 E		
	Venus	H	45 E		
	Point 4	H	50 D		
	Filtek Supreme	N	60 C		
	Grandio flow	N	60 C		
	Grandio	N	98 B		
	Filtek Z100	H	105 A		
da Silva and others[41b]	Filtek Supreme	N	99, A 135, B 94 A		Knoop hardness Curing modes: Standard: 650 mW/cm^2 output intensity (30 s) High intensity: 1000 mW/cm^2 (20 s) Ramped: 100 to 1000 mW/cm^2 (10 s) + 1000 mW/cm^2 (10 s)
	Filtek P60	H	103, A 141, B 94 A		

Table 5: Continued.

Study	Material	Category	Hardness[a]		Test Conditions
Kaminedi and others[59]	Filtek Z250	H	61 B		Vickers hardness
	Filtek Z350	N	67 A		
Cao and others[65]	Charisma Diamond	N	54 C		Vickers hardness following abrasive challenge
	Filtek Z250	H	79 B		
	Surefil	H	79 B		
	Filtek P 60	H	82 B		
	Clearfil AP-X	H	87 A		
Rastelli and others[58]	TPH[3]	N	53 B	46 C	Vickers hardness
	Filtek Supreme	N	72 A	56 B	
	Filtek Z250	H	72 A	71 A	
Thome and others[62b]	Filtek Supreme	N	Top surface Hardness A3.5: 76, 74, 61 A1: 83, 79, 67 B		Vickers hardness Shade: A1, A3.5 Curing distance: 0, 6, 12 mm
	Filtek Z250	H	A3.5: 90, 76, 71 A1: 98, 81, 68 A		
Suzuki and others[12c]	Tetric Evo Ceram	N	35 D		Knoop hardness
	Venus Diamond	N	45 C		
	Filtek Supreme XT	N	57 B		
	Grandio	N	80 A		
Marchan and others[69b]	Clearfil Majesty	N	33, 27, 28	26, 26, 26 D	Vickers hardness Curing mode and time: QTH: 495 mW/cm^2 for 20 s LED: 890 mW/cm^2 for 20 s LED: 890 mW/cm^2 for 10 s
	Tetric Evo Ceram	N	34, 33, 30	28, 33, 30 D	
	Ice	N	51, 51, 47	43, 45, 43 C	
	Filtek Z350	N	65, 61, 64	64, 59, 54 B	
	Grandio	N	73, 75, 72	70, 70, 66 A	

[a] Means with the same s letters within each study are not statistically different. For studies with multiple values, letter was used to indicate significant difference between different materials.
[b] Multiple values for each material property indicate the reported value under each test condition in the study.
[c] Approximate values are used since data were reported using a bar chart.

gy should be done in order to be able to directly compare results.

ABRASIVE WEAR

Wear has been defined as the gradual removal of material as a result of the interaction between two surfaces moving against each other.[70] Wear of resin composite has been reported to be dependent on filler loading and size in addition to the formulation of its resin matrix and the adhesion of fillers to the matrix.[27]

Several studies investigated abrasive wear of nanocomposites compared with hybrid and microfilled composites by measuring specimen thickness using calipers,[71] assessing surface roughness,[12] and measuring weight loss of tested samples following abrasion.[30] Table 6 shows abrasive wear values reported by the studies included in the current literature review.

Mitra and others[22] examined the wear rate of nanocomposites (standard and translucent) compared with hybrid and microfilled composites using a three-body wear test. The wear rate of the standard nanocomposite was equivalent to a hybrid but significantly lower than the other hybrid and microfilled composites. The translucent nanocomposite demonstrated equivalent wear values to the microfilled composite but was significantly lower than the other hybrid materials. Comparable results were shown by Cao and others,[65] who reported significantly lower volume loss of the tested nanocomposite compared with hybrid materials. Similarly, Yesil and others[72] reported comparable wear rate of a nanocomposite to that of a microfilled and a hybrid composite. Hamouda and Abd Elkader[30] reported that the nanocomposite tested in their study demonstrated a significantly lower wear value compared to the hybrid composite that was attributed to the higher filler loading and smaller particle size associated with the nanocomposites. Suzuki and

Table 6: *Abrasive Wear of Resin Composites (N, Nanocomposite; H, Hybrid; M, Microfilled)*

Study	Material	Category	Abrasive Wear[a]	Test Conditions
Mitra and others[22b]	Filtek Supreme standard	N	2.1 C	Three-body wear test Wear determined every 39,000 cycles (μm/39,000)
	Filtek Z250	H	2.4 C	
	Filtek A110	M	3.0 B	
	Filtek Supreme Translucent	N	3.1 B	
	Point 4	H	3.4 A	
	Esthet X	H	3.5 A	
	TPH Spectrum	H	3.6 A	
Hamouda and Abd Elkader[30]	Filtek Supreme	N	25 B	Two-body abrasion, then measuring weight loss (mg)
	Prime Dent	H	74 A	
Cao and others[65]	Charisma Diamond	N	6 C	Wear volume loss (mm^3)
	Filtek Z250	H	8 B	
	Filtek P60	H	8 B	
	Clearfil AP-X	H	8 B	
	Surefil	H	10 A	
Yesil and others[72]	Point 4	H	7 B	Simulated masticatory wear mechanism using human enamel as opposing cusp (μm)
	Heliomolar RO	M	12 AB	
	Filtek Supreme	N	14 AB	
	Premise	N	19 A	
Suzuki and others[12b]	Grandio	N	10 C	Tooth brushing abrasion test (μm)
	Venus Diamond	N	80 B	
	Filtek Supreme XT	N	90 B	
	Tetric Evo Ceram	N	600 A	

[a] Means with the same letters within each study are not statistically different.
[b] Approximate values are used since data were reported using a chart presentation.

others[12] submitted several commercial nanocomposites to an abrasion challenge. It was suggested by the authors that the nanocomposite, which displayed the lowest wear rate, behaves more like a hybrid composite, and its low wear was attributed to its densely packed fillers.[73]

On the other hand, Mayworm and others[74] investigated abrasive wear of a nanocomposite and a hybrid before and after storage in saliva for 62 days. Greater abrasive wear of the nanocomposite compared with a hybrid was reported. This was attributed to the larger interparticle space of the former leading to larger wear rates.

Several researchers have suggested that wear resistance behavior of composites is material dependent and cannot be predicted from only a material's filler loading or organic matrix composition.[75] However, the reported results suggest that several commercial nanocomposites have shown wear values that are lower than several hybrid composites. Also, a number of researchers reported comparable wear values between nanocomposites and microfilled composites that have been reported to display the lowest abrasive wear among resin composites.

SORPTION AND SOLUBILITY

Longevity of a restorative material in the oral environment is directly related to its resistance to degradation.[76] Therefore, the assessment of solubility and salivary sorption is essential to predict material behavior and clinical performance.[32,77] The influence of polymerization mode, curing times, storage media, and filler content on sorption and solubility have also been investigated.[1,32,77-79] Table 7 shows reported results from different studies and special testing conditions.

Da Silva and others[77] reported significantly higher sorption and solubility of a nanocomposite compared with a hybrid composite tested in their study when using two polymerization modes (conventional and ramped) (Table 7). The ramped polymerization mode was associated with a lower DC in both composites. Higher sorption and solubility of the nanocomposite was explained by the greater surface area of the nanofillers. This makes them more prone to ion leaching and hydrolysis of the silane coupling agent, leading to the filler particles becoming detached and lost. Higher values of salivary sorption of the nanocomposite were attributed to water accumula-

Table 7: *Sorption and Solubility Values (μg/mm³) of Resin Composites (N, Nanocomposite; H, Hybrid; M, Microfilled)*

Study	Material	Category	Sorption (μg/mm³)[a]	Solubility (μg/mm³)	Test Conditions
da Silvaand others[77b]	Filtek P60	H	6.7, D 7.04 C	0.38, C 0.43 B	Curing modes: Conventional: 850 mW/cm² (10 s) Ramped: 100 to 1000 mW/cm² (10 s and 1000 for 20 s)
	Filtek Supreme	N	7.35, B 8.74 A	0.41, B 0.49 A	
Kumar and Sangi[32b]	Filtek Z250	H	17.3, 23.5 B	1.5, 1.1 B	Storage period: 1 wk 13 wk
	Filtek Supreme translucent	N	18.7, 24.9 B	1.1, 1.0 B	
	Filtek Supreme body	N	23.6, 27.4 A	2.3, 3.6 A	
Shin and others[82b]	Grandio	N	11.4, 11.3 F	3.1, 0.8 E	Curing modes: DPSS laser: 400 mW/cm² Conventional: 800 mW/cm²
	Ceram X	N	15.3, 15.4 E	4.6, 0.9 D	
	Tetric Ceram	H	16.6, 15.7 D	5.2, 1.2 C	
	Filtek P60	H	17.4, 18.1 C	2.4, −1.4 F	
	Premise	N	20.7, 21.0 B	6.6, 1.6 A	
	Filtek Z350	N	24.1, 22.8 A	6.3, 1.0 B	
De Moraes and others[1]	Grandio	N	15.1 B	3.1 A	7-d storage in water
	Concept Advanced	N	17.3 B	3.1 A	
	Premise	N	18.1 AB	5.1 A	
	TPH[3]	N	26.4 A	2.9 A	
	Filtek Supreme XT	N	29.1 A	2.9 A	
	Filtek Z 250	H	30.7 A	1.9 A	
Almeida and others[78b]	Filtek P60	H	2.8, 8.9, 7.3, 4.0 B	2.4, 6.4, 3.4, 2.4 A	Storage media: Artificial saliva Listerine Plax fresh mint Plax
	Filtek Z350	N	14.1, 20.4, 11.9, 14.8 A	3.1, 6.2, 4.4, 3.0 A	

[a] *Means with the same letters within each study for each property are not statistically different. For studies with multiple values, one letter was used to indicate significant difference between different materials.*
[b] *Multiple values for each material property indicate the reported value under each test condition in the study.*

tion at the filler–matrix interface and inside the aggregates of the nanocomposite. Similarly, Kumar and Sangi[32] reported significantly higher water sorption and solubility for one nanocomposite compared with the other nanocomposite and a hybrid following 13 weeks of water storage. Furthermore, lower strength values were reported for the nanocomposite that showed the highest sorption and solubility values. The lower strength values of the nanocomposite were attributed to the poor silane penetration of the porous nanoclusters. This made the nanocomposite susceptible to degradation when stored in water. Lower sorption by the hybrid was attributed to the better coupling between filler content and matrix.[80] On the other hand, Lopes and others[81] demonstrated no influence of varying polymerization mode on sorption and solubility of a nanocomposite. This was attributed to the formation of a densely cross-linked polymer network due to the use of an adequate energy density in all the curing methods used. Similarly, Shin and others[82] reported no effect on sorption values of the tested composites when varying polymerization mode. One nanocomposite displayed the lowest sorption and second-lowest solubility compared to a hybrid composite. This was attributed to its high and dense filler content. Similarly, de Moraes and others[1] reported significantly lower sorption of a nanocomposite compared to a hybrid and other nanocomposites tested, while all tested composites displayed comparable solubility values. The authors suggest that results of water sorption and solubility are probably related to the nature of the organic matrix chemical rather than to the filler content of the material (Table 7).

The effect of using different storage media on sorption and solubility of resin composites was assessed by several researchers.[78,81,83] Almeida and others[78] and Lopes and others[81] demonstrated an influence of storage media on the sorption of resin composites tested. Negative values of solubility were

reported by researchers for a number of nanocomposites indicating weight gain masking the real solubility. Almeida and others[78] reported significantly higher sorption of a nanocomposite compared with a hybrid in Listerine (Warner Lambert Health Care, Eastleigh, UK), Plax fresh (Colgate-Palmolive, Guilford, UK), Plax (Colgate-Palmolive), and artificial saliva. The solubility of the nanocomposite and hybrid composites was comparable, with significantly higher values obtained when placed in Listerine and Plax fresh. Similar results regarding water sorption were shown by Curtis and others,[84] who investigated these properties after different storage periods of a nanocomposite and hybrid composite. It was suggested that the higher water sorption was related to the larger ratio of surface area to volume of the silica nanofillers and the hydrophilic nature of the polymeric matrix.[85]

Goncalves and others[79] assessed sorption and solubility of a nanocomposite and a hybrid and DC in simulated deep proximal cavities. This was done to investigate composite behavior in a situation similar to a clinical setting. Sorption and solubility were assessed for every 1-mm increment of the 5-mm-deep restoration in three immersion media: distilled water, artificial saliva, and lactic acid. The nanocomposite displayed a lower DC and significantly higher sorption and solubility values than the hybrid. Regardless of media type, the immersion of both resin composites presented an increase in solubility and sorption as a function of depth.

The previously mentioned data generally indicate higher sorption and solubility of nanocomposites. The number of studies investigating sorption and solubility of nanocomposites compared to hybrid and microfilled composites is still limited. Further investigations using test conditions that simulate a clinical setting and compare a wide range of materials are recommended to ascertain the performance of nanocomposites.

CLINICAL STUDIES

The clinical performance of nanocomposites has been investigated in numerous studies and was found to be comparable to that of other resin composites. The majority of these clinical trials used the modified USPHS criteria first described by Cvar and Ryge[86] and the US Public Health Service's modified Ryge criteria.[87] These criteria include retention, color match, marginal discoloration, anatomic form, recurrent caries, surface roughness, marginal adaptation, postoperative sensitivity, gross fracture, tooth integrity, gingival health, and proximal contact.

Several clinical studies extending from one to four years reported comparable performance between nanocomposites and hybrid composites in posterior teeth and noncarious cervical cavities.[88-102] There was no detection of restoration failure, good surface characteristics, good color match, and no postoperative sensitivity.[103-106] Better polishability and surface gloss retention in favor of the nanocomposites were reported and attributed to the reduced filler plucking and less wear of the nanofillers.[107-109] However, a number of studies reported a certain degree of deterioration in marginal quality over time with minor defects creating surface roughness in all composites tested.[93,109,110] Türkün and others[111] reported a high retention rate of the nanocomposite but a better color match of the polyacid-modified composite tested after two years. In a two-year evaluation, it was reported that beyond one year, a negative step occurred due to wear, in addition to staining of the composites tested.[94] Similarly, Dukic and others[102] reported deterioration of all composites tested after three years with regard to anatomic form, marginal integrity, and marginal discoloration, but these composites were still regarded as being clinically acceptable.

Several long-term clinical performance studies of nanocomposites ranging from five to 10 years have been published. Palaniappane and others[112,113] evaluated the five-year clinical performance of nanocomposite materials compared to hybrid composites in occlusal and posterior approximal cavities. There was no significant difference in the vertical and volumetric wear between one nanocomposite and a hybrid composite as reported by Palaniappane and others,[112] while another nanocomposite material showed lower volume loss compared to the hybrid composites tested by Palaniappane and others[113] after five years. This was explained by the densely packed nanofillers in the nanocomposite that offered protection to the softer resin matrix from the abrasive action of food particles.

Cetin and others[115] reported excellent five-year clinical performance of two nanocomposites when compared to two indirect composite materials. No restorations were rated unacceptable in any aspect of the evaluation. A nanocomposite was also compared to a hybrid material after six, eight, and 10 years.[116,117] The overall success rates of the nanocomposite were 88.1%, 98%, and 80%, respectively, with a comparable performance between the investigated composites.[116-118] The higher success rate at eight years compared with six years may be due to

the use of different nanocomposite material in each study. Furthermore, the inclusion criteria for recruited subjects differed in that high-caries-risk patients were not excluded from the six-year evaluation period study.[116] On the other hand, Frankenberger and others[118] included subjects with a high level of oral hygiene, which may have contributed to the reported higher success rate after eight years compared with six years. The authors reported no significant difference in the clinical behavior between the tested composite restorations. Furthermore, significant changes over time were found for all criteria evaluated.

On the basis of the results of the previous studies, it seems reasonable to conclude that there is no evidence yet that the nanocomposites perform clinically better than hybrid composites.

CONCLUSION

The current review of the published literature has shown that commercially available nanocomposite materials do not hold any significant advantage over hybrid composites in terms of strength and hardness. Furthermore, higher sorption and solubility values were found for nanocomposites compared with hybrid composites, and these might influence their clinical performance. On the other hand, the incorporation of nanofillers into resin composite materials was associated with lower abrasive wear of nanocomposites. However, attention should be focused on the resin matrix composition and not only the filler system to be able to assess abrasive wear behavior. In the current review, nanocomposites demonstrated acceptable clinical performance compared with hybrid resin composites for review periods ranging from one to 10 years. However, there was no definitive report of the superior performance of nanocomposites in the majority of evaluation criteria used.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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