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Investigation of the correlation between the different mechanical properties of resin composites

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The aim of this study was to investigate the relationship between the different mechanical properties with the filler fraction of various resin composites. Mechanical properties of eighteen different resin composites were investigated in this study; flexural strength (FS), flexural modulus (FM), fracture toughness (FT), compressive strength (CS), diametral tensile strength (DTS), Barcol hardness (BH), Vickers hardness (HV), and Knoop hardness (HK). The mean values of mechanical properties and the filler fractions (V_f) obtained from the literature and the manufacturer were analyzed using Pearson's correlation test at $p<0.01$. The relationships were compared with the data retrieved from previous studies. Strong correlations between V_f and BH/HV/HK and V_f and FM were evident in the results of the present study and these results were supported by the retrieved data from previous studies. The other relationships between mechanical properties, such as that between FS and FM and between CS and HV were not significant.

Keywords: Resin composite, Filler fraction, Mechanical properties, Correlation analysis

INTRODUCTION

Direct resin composite restorations have become the most important treatment option in the field of clinical dentistry due to a withdrawal trend of dental amalgam and an increased demand for esthetics. This situation was augmented by continuous development and improvement in the physical and mechanical properties of visible light-cured resin composite materials[1-4]. However, investigations on the clinical performance have reported fracture of resin composite restorations as the most prominent cause of failure[5-9]. Therefore, many studies have focused on evaluating the mechanical properties of resin composites and comparing them with the other properties.

The effect of filler fraction on the mechanical and physical properties of filler-matrix coupled composites has been well demonstrated in previous studies[10-12]. In particular, a very high degree of exponential correlation between filler volume and elastic modulus/flexural strength was demonstrated in a model composite resin[12]. Such a proportional relationship between the mechanical properties of composite resin has been observed in some earlier commercial composite resins[13]. The results of these studies support the claim that in a clinical sense, filler fraction can be used as a measure to quantity the mechanical properties of resin composites[12,14]. However, there is a need to reappraise these relationships in the newer and/or wider range of composite resins, since the relationship between mechanical properties and filler fraction is less clear[15,16].

Because of the complexity of loading in a clinical situation, it has been advocated that various test methods should be applied for evaluation of the mechanical performance of restorative materials[17,18]. Fracture resistance of brittle restorative materials has been frequently evaluated by measuring the flexural properties such as flexural strength and flexural modulus by a three-point bending test which has been adopted by international standards, including ISO 4049:2000 Polymer-based filling, restorative and luting materials[19]. Another important mechanical property for dental composite materials is the fracture toughness (FT), which indicates the relative resistance to crack propagation from the surface or inherent flaws in the materials[20]. Generally, mastication exerts compressive loading onto dental restorations. Hence, compressive strength (CS) and diametral tensile strength (DTS) tests have been widely used to evaluate fracture resistance of resin composites due to their ease of use in specimen fabrication and testing procedure[18,21], although they have not been adopted by ISO 4049. Vickers and Knoop microhardness (HV and HK) tests are simple methods for testing the surface mechanical properties and they have long been used to evaluate the degree of conversion, wear rate of resin composites and other physical properties of dental resin composites. Another hardness test used for resin composites is the Barcol hardness (BH) test by penetrating with a truncated conical needle[13,22,23].

Although a wide variety of fillers and resin matrices have been used in the current resin composites, they generally have a similar filler-matrix coupled composite system. It thus seems plausible that some trends can exist in the relationship between the mechanical properties of resin composites[13]. There is a large amount of data in the literature on the mechanical properties of resin

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composites which are measured by various test methods. Many studies have demonstrated some correlations between individual mechanical properties of resin composites, such as between HK and CS/DTS[13,24], HV and FM[25], FT and BH[22], HK and FT[26,27], CS and DTS[28], FS and DTS[29], and FS and FM/CS/DTS[16]. Recently, Takahashi *et al.*[30] conducted correlation analysis for the more integrated mechanical parameters including tensile properties, but this analysis was performed in six nano-hybrid and two other composites. However, these results have been generally reported using the limited number of test methods or materials.

In this study, various static mechanical properties of eighteen resin composites belonging to various categories were tested to investigate the relationship between filler fraction and mechanical properties of resin composites and between the different mechanical properties tested. In addition, these results were compared with the relationship between the reported mechanical properties data retrieved from the previous literatures. This attempt to identify the correlations between the different mechanical properties of resin composites and their relationship with filler fraction will provide the dentists with more practical information that will help in understanding the overall mechanical behavior of dental resin composites.

MATERIALS AND METHODS

The information regarding the eighteen resin composite materials investigated in this study is provided in Table 1. The filler contents were retrieved from the reported values in the literature and the manufacturers' data. For the flexural test, specimens were prepared using a split metal mold having internal dimension of 2×2×25 mm (*n*=6). Resin composites were packed into the mold and both the surfaces were covered by a transparent polyethylene film. The samples were light-polymerized for 40 s at three different points from both sides by LED curing gun (L.E.Demetron I, Kerr, CT, USA) with a tip diameter of 10 mm. The output of LED curing light measured by a portable radiometer (Kerr) was 700 mW/cm^2. All the resin flash of specimens was carefully trimmed using 600-grit SiC grinding paper and the accuracy of dimensions measured was ±0.01 mm. Then the specimens were stored in distilled water at 37ºC for 1 day before testing.

Flexure testing was conducted in a three-point bending apparatus with a 20-mm span at a crosshead speed of 0.75 mm/min according to ISO 4049. The samples were tested until fracture in a PC-controlled material testing machine (Instron 3344, Instron, MA, USA). The flexural strength (FS) and flexural modulus (FM) were calculated using the equations that have appeared in the literature[20]. Work of fracture (WOF, kJ/m^2) was calculated by dividing the area under the load-deflection curve by the cross-sectional area of the specimen[31-33].

Another metal mold having internal dimensions of 2×4×25 mm with a sharp steel blade insert (0.5×2

Table 1 Dental resin composites tested in this study

Type	Product	Code	Manufacturer	Batch number	Filler content wt%/vol%*
Microfilled	Metafill CX	MT	SUN Medical	KF1	42/26[a]
Hybrid	Spectrum TPH	SP	Dentsply	00329	77/57[b]
	Arabesk Top	AB	VOCO	09632	77/56[b]
	Charisma	CR	Heraeus Kulzer	11037	78/61[b]
Flowable	Revolution2	R2	Kerr	415169	52/41[c]
	Dyract flow	YF	Dentsply	040700	59/43[b]
	Denfil flow	DF	Vericom	FR4902133	60/37[m]
	Filtekflow	FF	3M ESPE	4GG	68/47[m]
Packable	Heliomolar HB	HB	Vivadent	F60722	67/46[m]
	Solitaire2	S2	HeraesKulzer	170229	75/58[b]
	Filtek P60	FP	3M ESPE	5YY	83/61[b]
	Surefil	SR	Dentsply	500125	82/66[b]
	Quixfil	QX	Dentsply	1843	86/66[b]
Nanofilled	Filtek supreme	FS	3M ESPE	4WA	79/60[b]
	Grandio	GR	VOCO	431218	87/71[m]
Ormocer	Admira	AD	VOCO	480061	78/60[b]
Compomer	Magicfil	MG	DMG	518219	63/40[m]
	F2000	FC	3M	20050120	84/67[b]

*Data from (Kim *et al.*, 2002)[a], (Ilie and Hickel, 2009)[b], (Bonillar *et al.*, 2003)[c], and the manufacturer[m].

mm) was used to fabricate specimens for evaluating fracture toughness. The single-edge notched beam (SENB) specimens (n=3) were cured and stored as per the procedures described above, and then loaded into the above mentioned flexural jig (20-mm span) at a crosshead speed of 0.25 mm/min. The fracture toughness (FT, K_{Ic}) was calculated with the equation indicated in ASTM E-399:1997[34].

Cylindrical specimens were prepared for testing the compressive strength (6 mm in height and 4 mm in diameter) and diametral tensile strength (4 mm in height and 6 mm in diameter) in the respective PTFE molds. The samples (n=6) were light-cured and stored as per the procedures described above. Both the compressive strength (CS) and diametral tensile strength (DTS) were determined by loading in using a mechanical testing machine (Instron 8871) at a crosshead speed of 0.75 mm/min. The CS and DTS values were calculated from the respective equations[20].

For performing various hardness tests, disk specimens (8 mm in diameter and 2 mm in height) were prepared using the same procedure. After light curing under transparent strip, hardness measurements were performed after 20 min post-curing without further polishing. Barcol hardness was measured using the digital Barcol hardness tester (HHP-2001, Bareiss, Oberdischingen, Germany) mounted on a test stand with an electronic display unit[33]. The Barcol hardness number (BH; 0–100) for specimens was averaged from five indentations on each disk (n=6). Vickers and Knoop hardness values were determined on one surface of different disk samples (n=4) at a load of 4.9 N for 20 s using a microhardness tester (HM-122, Mitutoyo, Tokyo, Japan) by exchanging the diamond indenter. The mean Vickers and Knoop hardness values (HV0.5/20 and HK0.5/20) for each disk were averaged from three indentations, respectively. The Barcol indentations on resin composites were observed after ultrasonication in acetone for 1 h by using a SEM (S-3000. Hitachi, Tokyo, Japan).

Statistical differences in the results for each mechanical property were analyzed by one-way ANOVA and Tukey-Kramer post-hoc multiple comparison's test at the level of α=0.05. Correlations between the filler content and the mean mechanical properties were investigated by using Pearson's correlation test using Statview version 5.0 (SAS Institute, Cary, NC, USA) at the p<0.01 level. The Pearson's tests were also performed for the mean data retrieved from many previous reports in the literature.

RESULTS AND DISCUSSION

The mean flexural strength, flexural modulus, work of fracture, and fracture toughness values for the investigated materials are listed in Table 2. The mean compressive strength, diametral tensile strength, Barcol hardness, Vickers hardness and Knoop hardness values are listed in Table 3. The statistical differences between the means at α=0.05 are shown in the respective tables. Among the tested materials, microfilled MT and compomer FC belonged to the lowest group for some mechanical properties, but interestingly MT and FC showed the highest mean values for CS and BH, respectively. However, the influence of the category of materials tested on the mechanical properties appeared to be less in the overall results, as indicate by Ilie and Hickel[16]. Table 4 shows the Pearson's correlation coefficient matrix between the mean values of the investigated mechanical properties and their filler fraction data. A high linear correlation was observed between the reported weight fraction (W_f) and the volume fraction (V_f) for the materials tested in this study (Pearson's r=0.97, p<0.01). Thus, it can be expected that the W_f and V_f can influence the mechanical performance of resin composites in a similar manner in this study.

Correlation between the filler fraction and the mechanical properties

Among the various mechanical properties investigated in this study, the FM (r=0.90) value was the most significantly correlated with V_f, followed by the hardness values (r>0.75) and DTS (r=0.71) (Table 4). A higher correlation between V_f and FM (*i.e.* elastic modulus) has been demonstrated in numerous previous studies. A well-fitted exponential correlation (r>0.90) was established between FM or dynamic modulus (DM) measured by a non-destructive test and V_f for the experimental resin composites in a previous study[12]. Similarly, high positive relationships between W_f/V_f and DM/FM have also been observed in the mean results of the commercial products[35-41]. These results were further supported by the strong relationship between filler content and the elastic moduli measured by compressive loading[42,43]. In a previous study investigating more than 70 resin composites, the FM value was more sensitively affected by the V_f value compared to the other mechanical parameters including FS and CS[16].

It has been shown that the HV value for model composites increases markedly with increasing filler fraction when the filler particles were silanated[44]. In this study, significantly high correlation coefficients were also observed for the filler fraction and all the three hardness values (r>0.80). Similarly, in commercial and experimental products, high correlations between V_f/W_f and BH/HV/HK could be seen in the data retrieved from numerous reports[13,35,38,39,45]. A previous study has demonstrated that surface hardness was significantly correlated with filler volume rather than size of filler[46].

For correlation between V_f and DTS, high correlation coefficients (r=0.83–0.89) were observed in the model composite with V_f ranging from 0% to 57%[47]. However, in highly filled hybrid composites over 60% in V_f, little variations were observed in the DTS values according to the filler content in previous studies[45,48,49]. Moreover, an investigation of a wide range of commercial products showed that DTS was insensitive to V_f, as compared to the relationship of FM or FS to V_f[16].

In this study, the FS, FT, and CS showed virtually no correlation with the V_f in the resin composites. In

Table 2 Fexural strength (FS), flexural modulus (FM), work of fracture (WOF), and fracture toughness (FT) of the tested resin composites

Code	FS (MPa)	FM (GPa)	WOF (kJ/m^2)	FT ($MPa\cdot m^{0.5}$)
MT	64.2 (3.0)	2.42 (0.15)	2.65 (0.37)	1.25 (0.02)
SP	145.2 (14.2)	9.16 (0.61)	3.23 (0.68)	2.42 (0.48)
AB	108.0 (23.5)	8.74 (0.48)	1.81 (0.76)	2.57 (1.08)
CR	107.0 (9.8)	8.11 (0.27)	1.99 (0.54)	1.30 (0.32)
R2	109.2 (17.3)	5.08 (0.53)	3.70 (1.49)	2.32 (0.07)
YF	80.4 (7.1)	4.74 (0.18)	1.87 (0.38)	1.58 (0.05)
DF	110.2 (3.4)	4.92 (0.18)	4.40 (0.58)	2.36 (0.30)
FF	125.7 (5.8)	5.62 (0.33)	5.51 (1.10)	2.33 (0.27)
HB	78.3 (10.6)	5.21 (0.24)	1.62 (0.50)	1.18 (0.19)
S2	101.2 (11.9)	7.30 (0.25)	2.04 (0.56)	2.08 (0.39)
FP	106.0 (24.2)	11.40 (0.89)	1.33 (0.62)	2.25 (0.64)
SR	79.2 (18.5)	11.50 (0.48)	0.64 (0.41)	2.15 (0.69)
QX	118.2 (3.1)	14.36 (0.52)	1.22 (0.09)	1.74 (0.36)
FS	118.9 (14.8)	9.88 (0.38)	2.02 (0.56)	2.33 (0.18)
GR	104.9 (14.8)	14.72 (0.54)	0.89 (0.27)	1.97 (0.34)
AD	114.4 (17.8)	8.29 (0.19)	2.35 (0.81)	1.69 (0.29)
MG	76.4 (12.3)	7.52 (0.58)	0.98 (0.36)	1.60 (0.62)
FC	45.2 (8.3)	13.36 (0.72)	0.42 (0.10)	0.99 (0.04)
Critical difference*	31.0	1.05	1.47	1.35

*Critical difference values of Tukey-Kramer post-hoc multiple comparison's test (α=0.05).

the experimental composites with the same matrix-filler system, the correlation between V_f and FS was significantly strong[12]. However, for the commercial products, other studies showed a very low or no correlation between V_f and FS[16,41,50-53], although one report revealed a good correlation (r=0.86, n=14)[35]. Even the FS value measured by a four-point flexural test showed no correlation (r=0.02) with V_f, while there was a significant correlation (r=0.89) between FM and V_f[54]. The WOF showed a negative correlation (r=−0.53) with V_f, indicating a decrease in the toughness of resin composites with an increase in the filler fraction. However, the WOF was increased when the resin matrix was reinforced by filaments or fibrilla-type of fillers[31,32]. The shape of fillers probably plays an important role in increasing the WOF.

Unlike the result in the present study, a significant correlation between V_f and FT in the commercial and experimental resin composites can be detected in the preceding reports (r=0.67–0.99)[35,39,41,55]. However, there was no correlation between V_f and FT in nine flowable composite resins with the V_f ranging from 42 to 55 vol%, which was measured by using a test configuration (SENB) similar to that in this study[56]. Also, same results could be observed in the posterior composites[57]. In a similar way, the mean CS value correlated with the V_f value in the experimental composites[11,47]. However, either of the group comprising for a wide range of early and contemporary resin composites did not show any significant correlation between the filler fraction and the mean CS value[16,24,38,58].

The results of the present study and those of some previous studies demonstrate that the elastic modulus and the hardness values are predictable as a function of V_f in both of the experimental and commercial resin composites. However, regarding the other mechanical properties, their relationship with V_f is often conflicting in the experimental and commercial resin composites. These findings indicate that the mechanical properties that are related to filler fraction of resin composites

Table 3 Compressive strength (CS), diametral tensile strength (DTS), Barcol hardness (BH), Vickers hardness (HV), and Knoop hardness (HK) of the tested resin composites

Code	CS (MPa)	DTS (MPa)	BH	HV0.5/20 (kg/mm^2)	HK0.5/20 (kg/mm^2)
MT	367.3 (30.7)	30.0 (3.4)	40.2 (4.6)	18.6 (1.2)	23.9 (2.5)
SP	294.8 (14.2)	47.5 (10.8)	71.5 (2.4)	59.5 (4.9)	54.4 (4.7)
AB	269.9 (22.1)	47.4 (3.1)	69.6 (1.0)	35.7 (0.8)	51.1 (4.4)
CR	330.8 (45.8)	49.2 (3.7)	67.9 (1.8)	35.7 (2.4)	45.7 (2.7)
R2	293.3 (38.8)	38.0 (4.2)	58.2 (2.7)	26.3 (4.6)	29.8 (1.2)
YF	298.5 (28.8)	43.5 (4.0)	71.3 (2.3)	46.0 (5.8)	51.7 (2.2)
DF	317.7 (24.0)	47.8 (4.5)	44.7 (1.4)	27.3 (5.1)	31.4 (2.7)
FF	306.2 (19.3)	51.3 (5.5)	56.6 (2.1)	47.5 (0.4)	32.4 (1.9)
HB	273.7 (12.5)	30.0 (6.2)	53.6 (1.2)	24.7 (0.7)	32.0 (1.2)
S2	347.0 (19.3)	51.7 (1.8)	68.3 (2.5)	36.4 (1.9)	42.2 (0.7)
FP	305.7 (22.1)	56.0 (7.7)	76.9 (2.9)	77.7 (1.2)	80.8 (2.2)
SR	332.9 (29.1)	58.8 (3.9)	77.9 (2.2)	56.9 (7.2)	59.7 (2.7)
QX	266.3 (12.6)	53.0 (7.8)	73.7 (3.4)	55.7 (5.1)	64.8 (1.8)
FS	377.6 (14.0)	61.6 (3.4)	76.0 (1.4)	54.6 (2.9)	61.6 (1.3)
GR	324.0 (30.8)	55.9 (11.2)	79.5 (2.5)	73.3 (3.5)	80.5 (1.1)
AD	304.5 (41.6)	46.4 (9.6)	66.8 (2.5)	44.5 (1.3)	46.3 (0.2)
MG	220.1 (28.2)	39.3 (3.0)	67.5 (2.8)	41.7 (2.2)	44.7 (1.2)
FC	281.6 (20.8)	42.6 (7.4)	85.3 (1.1)	54.2 (1.1)	54.3 (2.8)
Critical difference*	90.3	13.1	5.1	12.6	7.4

*Critical difference values of Tukey-Kramer post-hoc multiple comparison's test (α=0.05).

Table 4 Pearson's correlation coefficient matrix for the examined resin composites. Correlation coefficient values displayed in bold indicate a statistical significance at p<0.01 level (n=18)

	W_f	V_f	FS	FM	WOF	FT	CS	DTS	BH	HV	HK
Weight fraction (Wf)	1.00										
Volume fraction (Vf)	**0.97**	1.00									
Flexural strength (FS)	0.26	0.24	1.00								
Flexural modulus (FM)	**0.90**	**0.90**	0.08	1.00							
Work of fracture (WOF)	−0.50	−0.53	0.54	**−0.62**	1.00						
Fracture toughness (FT)	0.13	0.09	**0.69**	0.05	0.44	1.00					
Compressive strength (CS)	−0.06	0.04	0.25	−0.12	0.18	0.13	1.00				
Diametral tensile strength (DTS)	**0.72**	**0.71**	0.49	**0.64**	−0.12	0.56	0.34	1.00			
Bacol hardness number (BH)	**0.84**	**0.86**	−0.01	**0.86**	**−0.65**	0.07	−0.13	**0.65**	1.00		
Vickers hardness number (HV)	**0.77**	**0.75**	0.22	**0.82**	−0.39	0.24	−0.02	**0.72**	**0.81**	1.00	
Knoop hardness number (HK)	**0.80**	**0.79**	0.16	**0.86**	**−0.61**	0.19	−0.01	**0.71**	**0.85**	**0.92**	1.00

should be predicted cautiously. Further, the prediction of mechanical properties can get misled by inaccurate information on the filler fraction or the loading state in case of commercial products. The W_f of some materials provided by the manufacturers often shows discrepancies with the data measured by thermogravimetric techniques[15,35,59]. Although the reported W_f value was excellently correlated with the V_f value in this study, however, the correlations between W_f and V_f in some flowable or packable composite materials were low (r=0.40–0.51)[52,60]. Thus, a standardized method for determining the filler content will be needed to generalize these findings.

Correlation between the mechanical properties

Although the ISO 4049 standard for resin composites specifies only the requirement of the minimum FS value for the mechanical properties, the elastic modulus of resin composites can have more clinical relevance since it provides resistance of material to deformation, which is correlated with the clinical performance[61]. The FM of resin composites can be measured simply from the flexural stress-strain curve. Therefore, investigating the relationship between FS and FM would be useful for understanding the mechanical performance of resin composites.

Figure 1 presents the linear relationship between FS and FM as per the result of this study and the literature data. Although in all these studies, the materials were tested according to ISO 4049, contradictory trends were observed in the FS-FM relationship among composite materials; one group showed a high linear correlation (Fig. 1a; r=0.82–0.94, overall r=0.79)[15,35,50,62] and the other group showed a low linear correlation (Fig. 1b; r=0.1–0.5, overall r=0.30)[16,51,52] between FS and FM including this study. The results can be explained by the compositional difference between the examined resin composites according to material categorization. The group with a high linear correlation between FS and FM was observed in the data retrieved from a single category of resin composite, but the group with a low or no correlation was observed in the data retrieved from a relatively wide range of resin composites (including this study) or flowable composites. Even within a single category of resin composites, the correlation coefficient can be affected by resin composites showing unexpected mechanical behavior[30]. Further, a lack of clarity on the relationship between FS and FM can be attributed to low reliability of the ISO flexural test in resin composites[63,64]. As an example, Fig. 2 displays the mean FS values for one resin composite (Z100, 3M) that has been reported previously. Even though in all these studies, the materials were tested according to ISO 4049 in terms of specimen size, test configuration, and storage condition,

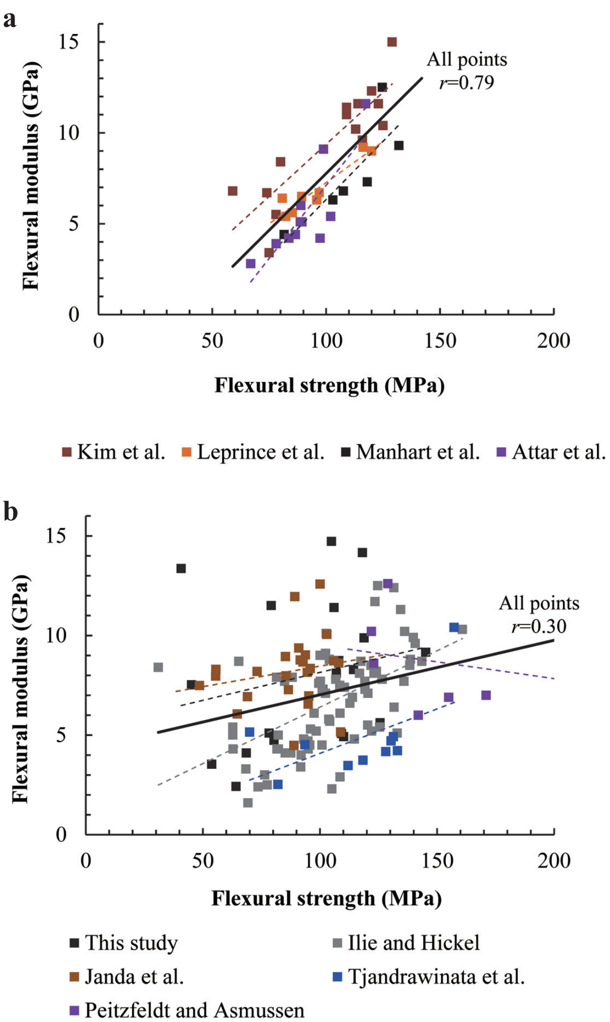

Fig. 1 Relationship between the flexural strength and flexural modulus in the literature data and in the results of this study.
a: group with a high correlation, b: group with a low or no correlation.

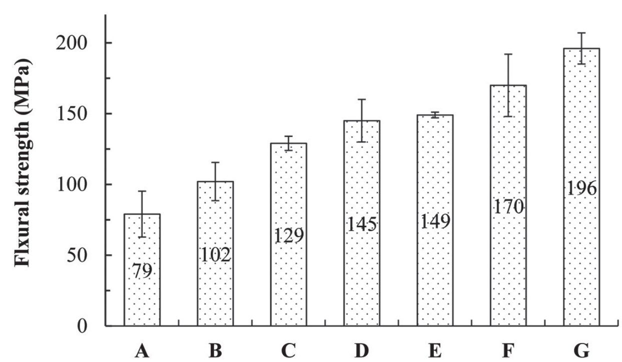

Fig. 2 Variation in the flexural strength value of one resin composite (Z100, 3M ESPE) reported in the literature.
A (Palin *et al.*, 2003), B (Bhamra *et al.*, 2010), C (Kim *et al.*, 2002), D (Hofmann *et al.*, 2000), E (Chung *et al.*, 2001), F (Choi *et al.*, 2000), G (Yap and Teoh, 2003).

the difference in the mean FS value among the reports was surprisingly large. Hence, the relationship between FS and FM for resin composites should be interpreted with caution.

On the other hand, the FS showed an intermediate but a statistically significant correlation (r=0.69, p<0.01) with the FT in this study (Fig. 3). This result is in agreement with that of the previous reports which show significant correlation coefficients for the FS-FT relation (r=0.53–0.88)[30,35,39,50]. However, the FT value was severely affected by precraking condition and test variables[26,55,65], and hence the relationship between FS and FT may need further verification. A reasonable correlation between WOF and FT can be expected since the WOF indicates the total energy required for flexural fracture, *i.e.*, the toughness of material. The correlation between the WOF values and the FT values was positive (r=0.44) for resin composites tested in this study.

Since compressive and diametral tensile strength tests have been commonly used for resin composites, the relationships of CS and DTS with the other parameters has been a cause of concern[28]. However, it has been indicated that the CS and the DTS tests cause a complex shear-tensile stress state within the specimens, possibly leading to inaccurate results[63]. As expected, the CS value did not correlate with all the mechanical properties that were investigated in the present study (Table 4). The finding of lack of correlation between the CS value and the other mechanical parameters was consistent with that in prior reports[16,24]. On the other hand, in this study, the DTS value showed a significant correlation with the FM value (r=0.64) and the V_f (r=0.71). The relationship between FS and DTS was not significant, which was consistent with the previous reports[16,29]. Rather, the results of this study and the previous data demonstrate that the DTS values are reasonably correlated (r=0.7–0.8) with the HV or HK values while the CS values showed no correlation with the hardness values, as shown in Fig. 4. In the literature, the CS tests often produce high standard deviations[16,28], which indicates their lower test reliability. The DTS values for resin composites were highly correlated with the tensile strength values tested using dumbbell-shaped specimens[30]. Generally, brittle materials are fractured by tensile stress, and it can thus be assumed that DTS is more relevant than CS in clinical situation. A poor correlation coefficient (r=0.34) between CS and DTS was recorded in this study, which is in agreement with the literature data showing a very low correlation coefficient (r<0.18)[16,24,28], thereby indicating that a high CS value for resin composites does not indicate a high DTS value[28].

The Barcol indentations produced severe radiating cracks with delamination in part of the resin composites around the indentations (Fig. 5), thereby indicating the different deformation mechanisms with Vickers or Knoop tests. Nonetheless, the three hardness values of the investigated resin composites were significantly correlated with each other (Table 4). The high correlation coefficients between HV and HK (r=0.92, p<0.01) and between HV/HK and BH (r=0.81–0.85, p<0.01) were supported by the literature data[13,66,67]. It thus appears that the hardness tests can be used interchangeably for assessing the other mechanical properties. Since BH can simply measure the hardness without surface polishing, it has often been used to evaluate hardness variables of resin composites using a conventional hand-held impressor[13,68-72]. An earlier study demonstrated a very narrow range of the conventional BH readings compared

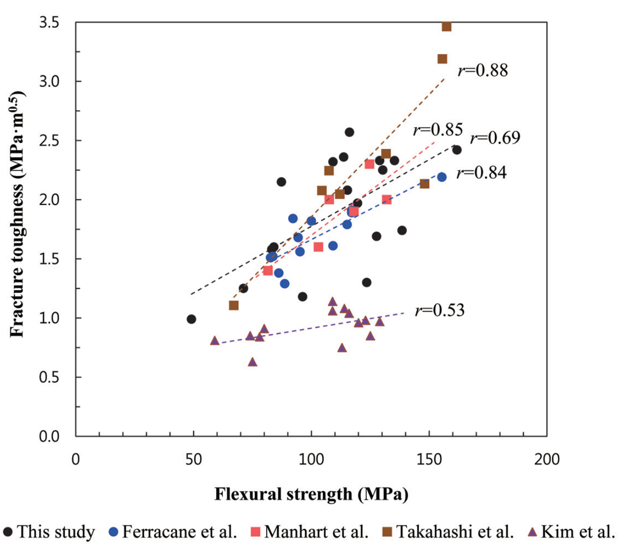

Fig. 3 Relationship between the flexural strength and fracture toughness in the literature data and in the results of this study.

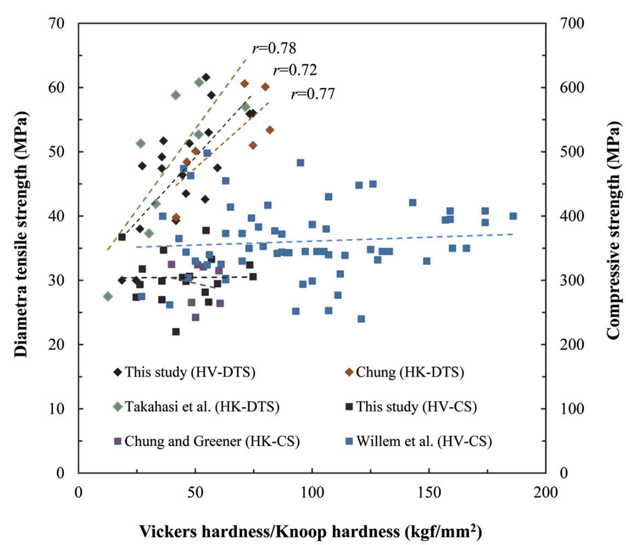

Fig. 4 Relationship between the Vickers/Knoop hardness and diametral tensile strength or compressive strength in the literature data and in the results of this study.

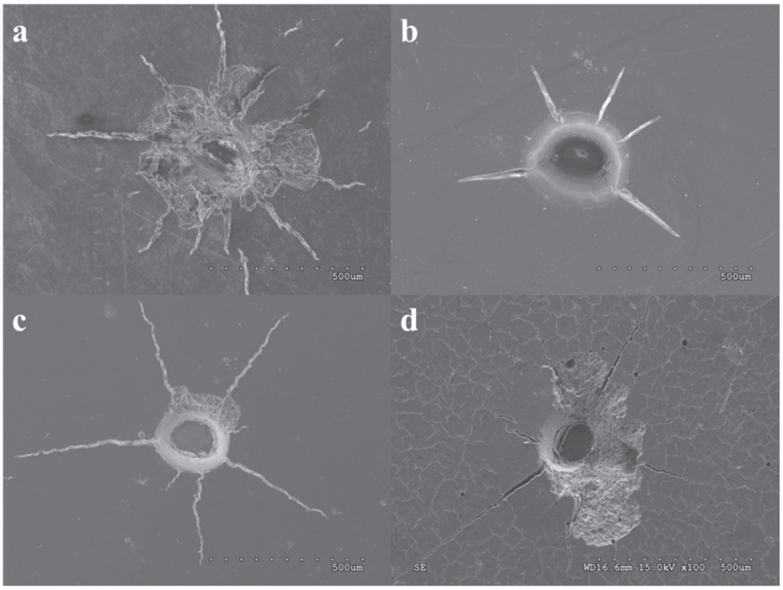

Fig. 5 Scanning electron micrographs of resin composite specimens indented by Barcol hardness tester.
a: MT (BH 40.2), b: DF (BH 44.7), c: GR (BH 79.5), d: FC (BH 85.3). Severe radiating cracks and delamination occurred around the indentations in all specimens.

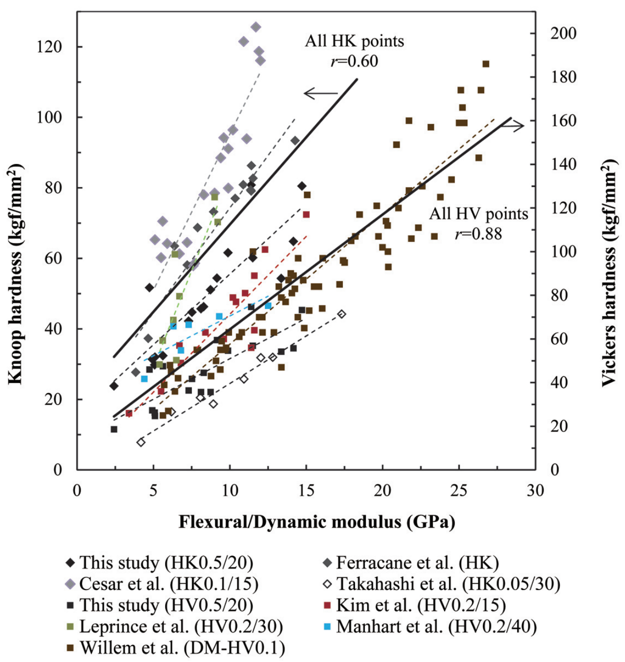

Fig. 6 Relationship between the flexural/dynamic modulus and Vickers/Knoop hardness in the literature data and in the results of this study.

to HV measurements[72]. In this study, the BH was measured by using a newer digital tester mounted on the test stand, which possibly resulted in an increased sensitivity of the measurement, although the degree of resultant surface damage was not discernible.

In this study, the correlations between all the hardness values and the FS values of the investigated composites were poor, while good correlation between HV and FS was found in the previous literature data[15,35,50]. This result might be attributed to the fact that the hardness measurements were performed at 20 min after curing; and the specimens were not fully cured. Similar to this result, the hardness values were also poorly correlated with the FT values in this study, and this finding was consistent with regression results from the literature data[22,35,50]. Correlation between HK and FT was demonstrated only in a single resin composite when it was tested at the same storage period[26,27]. Microhardness values of resin composites were dependent on several variables, such as light energy density, degree of conversion during setting[26,46,73], and therefore, generalization of their relationship needs further exploration[13,73].

In spite of this, the hardness values were significantly correlated with flexural modulus in this study (r>0.82, p<0.01). This result is supported by the data from numerous previous studies[15,30,35,38,39,50,74] as shown in Fig. 6. Within the given data, the overall correlation coefficient between FM and HV (r=0.88) was slightly greater than that between FM and HK (r=0.60). These findings indicate that hardness could be a powerful indicator for predicting the elastic modulus of various resin composites. Since both the hardness values and the FM values were strongly correlated with the V_f, this overall relationship can provide a useful inter-parameter measure for resin composites. The relationship between mechanical properties, such as between FS and FM and

between CS and HV, was not found to be significant in this study.

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