Comprehensive micro-mechanical characterization of experimental direct core build-up resin composites with different amounts of filler contents

Eugeni KOYTCHEV^{1,2}, Satoshi YAMAGUCHI³, Yuko SHIN-NO¹, Naoko SUZAKI¹, Motoki OKAMOTO³, Satoshi IMAZATO³, Maria DATCHEVA² and Mikako HAYASHI¹

¹ Department of Restorative Dentistry and Endodontology, Osaka University Graduate School of Dentistry, Suita, Japan

² Institute of Mechanics, Bulgarian Academy of Sciences, Sofia, Bulgaria

³ Department of Biomaterials Science, Osaka University Graduate School of Dentistry, Suita, Japan

Corresponding author, Eugeni KOYTCHEV; E-mail: koytchev@imbm.bas.bg

Dual-cured resin-based composites are gaining popularity as core build-up materials. Physical and elastoplastic characteristics of new experimental core build-up materials with variable filler contents (+2.5 and +5 wt%) were investigated using classic macroexperiments and nanoindentation. Flexural fracture strength increased from 91.7 ± 11.8 to 114.1 ± 9.1 and 116.6 ± 14.7 MPa in the +2.5 and +5 wt% groups, respectively; similarly, elastic moduli increased from 12.6 ± 0.9 to 15.4 ± 1.2 and 15.3 ± 2.0 MPa, respectively. Fracture toughness increased from 1.82 ± 0.60 to 2.28 ± 0.53 and 2.67 ± 0.88 MPa $\cdot$ m^{1/2} for the +2.5 and +5 wt% groups, respectively; indentation hardness increased significantly from 0.45 ± 0.03 to 0.55 ± 0.04 and 0.60 ± 0.10 GPa, respectively. The addition of +5 wt% filler content led to a mechanically superior material; the addition of +2.5 wt% filler led to better reliability.

Keywords: Core build-up materials, Fillers, Flexural strength, Fracture toughness, Nanoindentation

INTRODUCTION

The restoration of endodontically treated or severely broken down teeth, which in most cases are mechanically compromised, is required to compensate for the considerable bulk loss of hard tissues. There are many studies that have focused on the restoration of teeth after endodontic procedures^{1,2}. A core build-up is a restoration that facilitates a subsequent extracoronary restoration. Traditionally, metal cores were used², but because of the difference in elastic moduli between metal and dentin, stress concentrations leading to root fractures resulted³. To overcome this problem, composite resin materials that match the dentin modulus were developed⁴. According to a very recent nationwide survey in Germany, adhesive composite core build-ups were the predominant treatment approach to restore endodontically treated teeth (75%)⁵. However, defects and flaws in these materials often lead to catastrophic failures⁶. In the constant pursuit of improved mechanical properties, manufacturers are continually releasing materials with new and advanced formulations. The performances of these materials under oral conditions are related to their physicochemical properties. Undoubtedly, the ability of a core build-up restoration to tolerate fractures is related to its composition and filler volume. It has been demonstrated that increased filler loading at a threshold of approximately 55–57% by volume resulted in higher fracture toughness^{7–9}.

Because of the great variety and complex nature of forces in the oral cavity, many different methods for the mechanical characterization of restorative materials

have traditionally been employed. These include three-point bending (ISO 4049), tensile fracture strength testing¹⁰, and indentation and nanoindentation hardness methods^{11,12}. Fracture toughness (K_{IC}) is one of the most important measures of a material's properties and is a direct indication of the amount of stress that a material is capable of bearing prior to failure. There are many methods for assessing K_{IC} ; single-notch and chevron-notched rods are most commonly employed¹³. Recently, a fracture toughness method using notchless triangular prisms (NTPs) as specimens was proposed to avoid the inconvenience and shortcomings associated with placing a notch¹⁴.

The aim of this study was to evaluate a newly developed experimental direct core build-up material mechanically and micromechanically with different amounts of filler loading (+2.5 and +5 wt%). The null hypothesis tested was that there is no difference in mechanical or micromechanical performance between materials with variable filler loading contents.

MATERIALS AND METHODS

This study employed an experimental core build-up material based on the commercially available Clearfil DC Core Automix One (74 wt% filler load, Kuraray Noritake Dental, Tokyo, Japan) with two different amounts of filler content presented as weight percentages (+2.5 and +5 wt%). The chemical formulations of the materials used are shown in Table 1.

Flexural fracture strength

The estimation of the flexural fracture strength was conducted in a three-point bending test by means of a

Color figures can be viewed in the online issue, which is available at J-STAGE.

Received Jun 8, 2018; Accepted Nov 19, 2018

doi:10.4012/dmj.2018-190 JOI JST.JSTAGE/dmj/2018-190

Table 1 Chemical compositions

Product name [code] and manufacturer	Materials [lot no.]	Components
Clearfil DC Core Automix One [DC] (filler load 74 wt%) Kuraray Noritake Dental, Tokyo, Japan	6Q0202	silanated barium glass filler, silanated silica, Bis-GMA, TEGDMA, CQ, chemical catalyst, accelerators
Clearfil DC Core Automix One [DC + 2.5 wt% filler] Kuraray Noritake Dental	160218	silanated barium glass filler, silanated silica, Bis-GMA, TEGDMA, CQ, chemical catalyst, accelerators
Clearfil DC Core Automix One [DC + 5 wt% filler] Kuraray Noritake Dental	160219	silanated barium glass filler, silanated silica, Bis-GMA, TEGDMA, CQ, chemical catalyst, accelerators

Bis-GMA: bisphenol-A-diglycidyl methacrylate; TEGDMA: triethyleneglycol dimethacrylate; CQ: camphorquinone

universal testing machine (Autograph AG-IS 20 KN, Shimadzu, Kyoto, Japan) conforming to the ISO 4049 standard. Twenty beam-shaped specimens of each material were obtained using a custom-made metallic mold (2×2×25 mm) pressed between transparent plastic strips and glass to extrude excess material. After light polymerization for 4×20 s from the top and bottom sides with an LED device (wavelength, 380–430 nm; light output intensity, 1,000+400/–0 mW/cm²; PenCure 2000; J. Morita Mfg., Kyoto, Japan) and storage in distilled water at 37°C for 24 h, the specimens were subjected to complete failure in a three-point bending test at a crosshead speed of 0.5 mm/min. The flexural fracture strength was calculated using the following equation:

$$S_{max} = \frac{3Pl}{bd^2}$$

where P is the added load, l is the outer span length, b is the specimen width, and d is the specimen thickness.

Fracture toughness (K_{IC})

Twenty NTP specimens were prepared for each material group by using a custom-made metallic mold (6×6×6×12 mm) under the same pressing, polymerizing, and storage protocol as for flexural fracture testing. The specimens were then secured in custom-designed grips and subjected to complete failure in tensile load mode (EZ-Test, Shimadzu) at a crosshead speed of 0.1 mm/min. Each sample was scorched at the location of the tensile forces to create an approximately 0.1-mm-deep crack initiation point. The relationships that were used to calculate the K_{IC} value were proposed by Barker¹⁵⁾ and adopted by ASTM standard E1304. The equation is as follows:

$$K_{IC} = \frac{P_{max}}{D\sqrt{W}} Y_{min}$$

where: P_{max} =the maximum load at fracture, D =the specimen diameter (12 mm), W =the specimen length (10.5 mm), and Y_{min} =the minimum of the dimensionless

stress intensity factor coefficient (=28) as reported by Bubsey *et al.*¹⁶⁾ and proposed by Ruse *et al.*¹⁴⁾. The assembly of the NTP specimen and specimen holder is shown in Fig. 1.

Indentation hardness (H_{IT}) and the reduced elastic modulus (E_{IT})

Three specimens with approximate sizes of 4×4×2 mm were prepared (one for each material). The large surfaces were then fine-polished using a polishing device (EcoMet 3000, Buehler, Lake Bluff, IL, USA) using 800, 1000, 1200, 1500, and 2000-grit SiC papers and paper polishing pads under alumina polishing paste slurries of particles with decreasing sizes (1, 0.3, and 0.05 μm) to create a smooth surface suitable for the nanoindentation study. The specimens were then inspected under a stereoscopic zoom microscope (SM-Z 200, Nikon, Tokyo, Japan) prior to testing to check the integrity and quality of the polished specimens. The nanohardness and indentation elastic moduli of the resin composite were estimated by nanoindentation equipment (Nanoindenter G200, Keysight Technologies, Santa Rosa, CA, USA). The method of indentation used in this study is a load controlled method and the loading program is cycles loading with number of cycles equal to five. The indenter tip approaches the surface and when the indenter senses the surface, the cyclic loading/unloading begins. For each cycle, the indenter penetrates the surface for 10 s until reaching the maximum load for the current cycle followed by 10 s hold time and unloading of 90% of the maximum applied load reached during the current loading cycle. After the last cycle, the final load at unloading is held constant for 75 s to account for the thermal drift. The indenter is then withdrawn completely and ready to move into position for the next indentation test.

The maximum loads in all tests were 500 mN (nine indentations per sample; the maximum force achieved within five loading-unloading cycles). A distance of 100 μm was allowed between indentations to avoid any influence of residual stresses from adjacent indentations. The indentation modulus E_{IT} and hardness H_{IT} were calculated using the unloading part of the measured

Fig. 1 NTP specimen geometry and testing assembly.

Fig. 2 Schematic presentation of the nanoindentation experimental procedure.

value from the indentation test load-displacement curve as shown in Fig. 2. The equations to derive these mechanical characteristics are¹⁷⁾:

$$H_{IT} = \frac{P_{max}}{A(h_c)}, \quad (1)$$

$$E_{IT} = (1 - \nu_s^2) \left[\frac{2\beta}{S} \sqrt{\frac{A(h_c)}{\pi}} - \frac{1 - \nu_i^2}{E_i} \right]^{-1} \quad (2)$$

For a Berkovich indenter tip, the coefficient $\beta = 1.034$, P_{max} is the maximal applied force, ν_s is the Poisson ratio for the specimen (in our case, $\nu_s = 0.25$), and ν_i and E_i are the Poisson ratio and elastic modulus of the diamond tip, respectively. The projected area of contact between the indenter and specimen as a function of the contact depth h_c is introduced by the following approximation¹⁷⁾:

$$A(h_c) \approx C_0 h_c^2 + C_1 h_c + C_2 h_c^{1/2} + C_3 h_c^{1/4} + C_4 h_c^{1/8} + C_5 h_c^{1/16} \quad (3)$$

The coefficients in equation (3) are determined by a calibration procedure that consists of a nanoindentation experiment on a standardized quartz sample (fused silica) with a known elastic modulus and hardness independent of the indentation depth.

Weibull analysis

The Weibull statistical analysis method was used to estimate the characteristic K_{IC} , characteristic fracture strength, and reliability of each material. In the Weibull statistical analysis, the probability of fracture P_f is related to the fracture stress σ by the following exponential relationship¹⁸⁾:

$$P_f = 1 - e^{[-(\frac{\sigma - \sigma_u}{\sigma_0})^m]}$$

This is known as the Weibull three-parameter strength distribution. The threshold stress parameter, σ_u , represents the minimum stress below which a test specimen will not break. The scale parameter or characteristic strength σ_0 is dependent on the stress configuration and test specimen size. The distribution shape parameter m is the Weibull modulus. In order to analyze the results with Weibull statistics, 20 specimens were prepared for each group¹⁹. The Weibull modulus (m), represented by the slope of the curves, indicates the reliability of each material (the steeper the curve, the more reliable the material). Characteristic Weibull K_{IC} and Weibull fracture strength values were obtained from the plot at the 63.2nd percentile. An ANOVA and Tukey's test ($\alpha < 0.05$) were also performed to compare the results.

Scanning electron microscopy (SEM) observations of the fractured surfaces

Selected fractured specimens from the flexural fracture testing and NTP tensile testing were sputter-coated for SEM (JEOL JSM 6390 LV, Tokyo, Japan) observation of the fractured surfaces. All fractured surfaces were observed under SEM with magnifications ranging from $\times 50$ to $\times 5,000$.

RESULTS

The results are summarized in Tables 2, 3, and 4 and in the Weibull plot in Fig. 3. The different superscript letters indicate statistically significant difference between groups ($\alpha \leq 0.05$). Generally, with an increase in filler content, the fracture strength increased significantly from 91.72 ± 11.8 to 114.10 ± 9.1 MPa for DC+2.5 wt% and to 116.64 ± 14.7 MPa for DC+5 wt%. The same tendency was observed for the elastic moduli and indentation hardness. The elastic moduli increased from 12.63 ± 0.92 to 15.36 ± 1.2 GPa for DC+2.5 wt% and to 15.31 GPa for DC+5 wt%, while the indentation hardness increased from 0.45 ± 0.03 to 0.55 ± 0.04 and 0.57 ± 0.11 GPa for DC+2.5 wt% and DC+5 wt%, respectively. The probabilities of fracture for the tested groups of specimens are presented in Fig. 3 below. The Weibull moduli (m), defined by the slopes of the curves, showed that the DC+2.5 wt% specimens were the most reliable in both the fracture strength and fracture toughness tests.

Figure 4 shows typical examples of fractured specimen surfaces from both fracture strength and NTP fracture toughness testing. Note the air bubbles inclusions with the increase of filler amount (arrowed).

The indentation imprints, indentation moduli, and hardnesses for five different penetration loads are presented in Fig. 5 below.

The materials were tested in cyclic mode under five

Table 2 Fracture strength and Weibull statistical analyses of core buildup materials

Material	Fracture strength (MPa) Mean (SD)	Weibull modulus (m)	Characteristic Weibull fracture strength (in MPa)
DC	91.72 (11.8) ^a	9.28	4.68
DC+2.5 wt%	114.10 (9.1) ^b	15.03	4.84
DC+5 wt%	116.64 (14.7) ^b	9.47	4.92

Table 3 Fracture toughness (K_{IC}) and Weibull statistical analyses of core materials

Material	K_{IC} (in MPa $\cdot$ m ^{1/2}) Mean (SD)	Weibull modulus (m)	Characteristic Weibull K_{IC} (in MPa $\cdot$ m ^{1/2})
DC	1.82 (0.60) ^a	3.00	1.05
DC+2.5 wt%	2.28 (0.53) ^{ab}	5.18	1.10
DC+5 wt%	2.68 (0.88) ^b	3.66	1.37

Table 4 Indentation hardness (H_{IT}) and reduced elastic moduli (E_{IT}) of core materials

Material	Indentation hardness H_{IT} (in GPa) Mean (SD)	Reduced elastic modulus E_{IT} (in GPa) Mean (SD)
DC	0.45 (0.03) ^a	12.63 (0.92) ^a
DC+2.5 wt%	0.55 (0.04) ^b	15.36 (1.20) ^b
DC+5 wt%	0.57 (0.11) ^b	15.31 (2.01) ^b

Fig. 3 Weibull plots of K_{IC} results a) and fracture strength b).

Fig. 4 Scanning electron micrographs of fractured surfaces of DC, DC+2.5, and DC+5 wt% at ×50, ×1,000, and ×5,000 magnifications. Bubble inclusions are observed (arrow).

different loads to investigate the presence of eventual inhomogeneity with depth.

DISCUSSION

The three-point bending test is based on ISO specification 4049:2000 for polymer-based restorative materials and is commonly employed in dental materials research²⁰⁻²². This flexural bending test is usually recommended because the fabrication of specimens and load application

are quite simple.

Fracture is one of the main reasons for failures of dental composites in clinical practice²³. This usually occurs through pre-existing cracks and irregularities under tensile stress. These irregularities may be due to microstructural imperfections or bubble inclusions during mixing or insertion of the material²⁴.

In this study, the fracture strength was associated with the filler content of the core build-up material. Generally, an increase in fracture strength was observed

Fig. 5 Indentation imprints a); moduli, and hardnesses under five different penetration loads b).

with an increase in filler content in wt% (ANOVA and Tukey's test; $p < 0.05$). The observed increases as compared with the control group were 24 and 28% for DC+2.5 and DC+5 wt%, respectively. This is in good agreement with the findings of Kim *et al.*, who associated pre-polymerized filler particles with low filler content and poor mechanical properties⁹. Furthermore, the presence of TEGDMA in the composite matrix composition has been linked to a significant decrease in the flexural strength of the material; surprisingly, it has also been linked to an increase in the modulus of elasticity²⁵.

The K_{IC} values were determined in this study by using a relatively new and effective NTP method, which includes a simple and reproducible procedure for specimen preparation. The tendency here was similar to that observed for fracture strength. A 5 wt% increase in filler led to a 47% tougher material as compared with the control (ANOVA and Tukey's test; $p < 0.05$).

The results from the nanoindentation testing were also affected by filler content. Figure 5 depicts the imprints and surfaces of three samples. The calculated indentation moduli and hardnesses under five different loads are also shown in Fig. 5. It can be concluded that the mechanical characteristics of the samples with increased filler contents were superior compared with those of the control. The samples with higher filler content had a more homogeneous distribution of the elastic modulus and hardness with depth. There was no significant difference in the mechanical properties of the samples with increased filler content but we can still speculate that the DC+5 wt% material with the higher filler content was stiffer than the DC+2.5 wt% material.

The Weibull statistical analysis was used to estimate the characteristic K_{IC} , characteristic fracture strength, and reliability of each material. It is often noted that dental restorative composites, while popular in terms of esthetics and biocompatibility, are susceptible to brittle fracture¹⁸. For these materials, Weibull statistics are recommended. The Weibull modulus (m), given by the slopes of the curves (Fig. 3), indicates the reliability of each material (the steeper the curve, the more reliable the material). The addition of 2.5 wt% filler content led to the most reliable material.

SEM observation of the fractured surfaces from NTP testing revealed some bubble inclusions with increased filler content. This might be a possible explanation for the not-so-reliable nature of the DC+5 wt% material. On the other hand, the manipulative and handling abilities of the materials were not affected by the addition of filler particles.

Generally, the mechanical properties improved with an increase in filler content. There are some plausible mechanisms for this phenomenon. Some authors explain it with the crack bowing effect, resulting from pinning by the filler particles and increased energy at the crack tip^{26,27}, while others suggest crack branching, thereby increasing the crack surface area and resultant energy²⁸.

Although, the present study aims to focus at the micro-mechanical properties of core build-up materials, some effects of the filler contents regarding adhesion to the tooth substrate and polymerization are worth discussing. High inorganic contents were associated with low polymerization stress values, which is attributable

to the reduced shrinkage in highly filled composites²⁹⁾. Our specimen preparation protocol employed light curing from top and bottom sides. This actually differs from the procedure of polymerization that is typically employed in a clinical situation, where it is being done from one side only. A recent study³⁰⁾ revealed that in Clearfil DC Core Automix One, the degree of conversion showed no statistical difference between self and dual cured modes.

CONCLUSION

Within the limitations of this study, it can be concluded that an increase in filler contents with 2.5 and 5 wt% of the control core build-up material (Clearfil DC Core Automix One) led to improved mechanical properties. Regarding reliability, the 2.5 wt% increase in filler yielded the most reliable material and could be the preferred choice for clinicians when strength and toughness are of primary importance. Further studies are also warranted to reveal the clinical longevity of these materials.

ACKNOWLEDGMENTS

All materials used in this study were generously donated by Kuraray Noritake Dental. This study was supported by a Grant-in-Aid from the Ministry of Education, Science, and Culture of Japan [grant numbers KAKENHI JP16K20454 and JP17H04382].

REFERENCES

- 1) Kaur J, Sharma N, Singh H. In vitro evaluation of glass fiber post. *J Clin Exp Dent* 2012; 4: e204-e209.
- 2) de Medonça LM, Pegoraro LF, Lanza MDS, Pegoraro TA, de Carvalho RM. Effects of coronal substrates and water storage on the microhardness of a resin cement used for luting ceramic crowns. *J Appl Oral Sci* 2014; 22: 287-293.
- 3) Hegde J, Ramakrishna, Bashetty K, Sreirekha, Lekha C. An in vitro evaluation of fracture strength of endodontically treated teeth with simulated flared root canals restored with different post and core systems. *J Conserv Dent* 2012; 15: 223-227.
- 4) Stewardson DA, Shortall AC, Marquis PM. The effect of clinically relevant thermocycling on the flexural properties of endodontic post materials. *J Dent* 2010; 38: 437-442.
- 5) Naumann M, Neuhaus KW, Kölpin M, Seemann R. Why, when, and how general practitioners restore endodontically treated teeth: a representative survey in Germany. *Clin Oral Investig* 2016; 20: 253-259.
- 6) Thomaidis S, Kakaboura A, Mueller WD, Zinelis S. Mechanical properties of contemporary composite resins and their interrelations. *Dent Mater* 2013; 29: 132-141.
- 7) Bayne SC, Heymann HO, Swift EJ Jr. Update on dental composite restorations. *J Am Dent Assoc* 1994; 125: 687-701.
- 8) Kim KH, Ong JL, Okuno O. The effect of filler loading and morphology on the mechanical properties of contemporary composites. *J Prosthet Dent* 2002; 87: 642-649.
- 9) Ilie N, Hickel R, Valceanu AS, Huth KC. Fracture toughness of dental restorative materials. *Clin Oral Investig* 2012; 16: 489-498.
- 10) Bonilla ED, Mardirossian G, Caputo AA. Fracture toughness of various core build-up materials. *J Prosthodont* 2000; 9: 14-18.
- 11) Fischer H, Marx R. Fracture toughness of dental ceramics: comparison of bending and indentation method. *Dent Mater* 2002; 18: 12-19.
- 12) Sato M, Fujishima A, Shibata Y, Miyazaki T, Inoue M. Nanoindentation tests to assess polymerization of resin-based luting cement. *Dent Mater* 2014; 30: 1021-1028.
- 13) Ruse ND. Fracture mechanics characterization of dental biomaterials. In: Curtis RV, Watson TF, editors. *Dental biomaterials: Imaging, testing and modeling*. Cambridge, UK: Woodhead Publishing; 2008, p. 261-293.
- 14) Ruse ND, Troczynski T, MacEntee MI, Feduik D. Novel fracture toughness test using a notchless triangular prism (NTP) specimen. *J Biomed Mater Res* 1996; 31: 457-463.
- 15) Barker LM. Short bar specimen for KIC measurements. In: Freiman SW, editor. *Fracture Mechanics Applied to Brittle Materials*. ASTM STP 678. American Society for Testing and Materials; 1979, p. 73-82.
- 16) Bubsey RT, Munz D, Pierce WS, Shannon JL Jr. Compliance calibration of the short rod chevron-notch specimen for fracture toughness testing of brittle materials. *Int J Fracture* 1982; 18: 125-133.
- 17) Oliver WC, Pharr GM. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *J Mater Res* 1992; 7: 1564-1583.
- 18) Quinn JB, Quinn GD. A practical and systematic review of Weibull statistics for reporting strength of dental materials. *Dent Mater* 2010; 26: 135-147.
- 19) Nohut S, Lu C. Fracture statistics of dental ceramics: discrimination of strength distributions. *Ceram Int* 2012; 38: 4979-4990.
- 20) Chung SM, Yap AU, Chandra SP, Lim CT. Flexural strength of dental composite restoratives: comparison of biaxial and three-point bending test. *J Biomed Mater Res B Appl Biomater* 2004; 71: 278-283.
- 21) Palin WM, Fleming GJ, Marquis PM. The reliability of standardized flexure strength procedures for a light-activated resin-based composite. *Dent Mater* 2005; 21: 911-919.
- 22) Yap AU, Teoh SH. Comparison of flexural properties using ISO and mini-flexural tests. *J Oral Rehabil* 2003; 30: 171-177.
- 23) Manhart J, Chen H, Hamm G, Hickel R. Review of the clinical survival of direct and indirect restorations in posterior teeth of the permanent dentition. *Oper Dent* 2004; 29: 481-508.
- 24) Bona AD, Anusavice KJ, DeHoff PH. Weibull analysis and flexural strength of hot-pressed core and veneered ceramic structures. *Dent Mater* 2003; 19: 662-669.
- 25) Asmussen E, Peutzfeldt A. Influence of UEDMA, BisGMA and TEGDMA on selected mechanical properties of experimental resin composites. *Dent Mater* 1998; 14: 51-56.
- 26) Lange FF. Fracture energy and strength behaviour of a sodium borosilicate glass-Al₂O₃ composite system. *J Am Ceram Soc* 1971; 54: 614-620.
- 27) Lange FF, Radford KC. Fracture energy of an epoxy composite system. *J Mater Sci* 1971; 6: 1197-1203.
- 28) Kim KH, Park JH, Imai Y, Kishi T. Microfracture mechanisms of dental resin composites containing spherically-shaped filler particles. *J Dent Res* 1994; 73: 499-504.
- 29) Gonçalves F, Kawano Y, Braga RR. Concentration stress related to composite inorganic content. *Dent Mater* 2010; 26: 704-709.
- 30) Karakis D, Yildirim-Bicer AZ, Dogan A, Koralay H, Cavdar S. Effect of self and dual-curing on degree of conversion and crosslink density of dual-cure core build-up materials. *J Prosthodont Res* 2017; 61: 210-216.