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THESIS APPROVAL PAGE FOR MASTER OF SCIENCE IN ORAL BIOLOGY

Title of Thesis: The effect of depth-of-cure on the flexural strength of bulk fill composites

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Master of Science Degree
June 11, 2020

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14 May 2020

THE EFFECT OF DEPTH-OF-CURE ON THE FLEXURAL STRENGTH OF BULK FILL COMPOSITES

A manuscript
Presented to the Faculty of the Advanced Education in General Dentistry, Two-Year Program,
United States Army Dental Health Activity, Schofield Barracks, HI
And the Uniformed Services University of the Health Sciences – Post Graduate Dental College
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Oral Biology

By

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ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my AEGD Program Director, COL Lisa Yarbrough; Assistant Director, LTC Brandon Gage; Research Mentor COL Wen Lien, Research Assistant CPT Min Ju Yi and Statistician Mr. Michael Lustik for their insight, support and guidance throughout this research project.

Most of all, thank you to my loving wife Mandy and children Addie, Wesley, Daniel, and Jackson. Your love is immeasurably important to me and is the underlying foundation which allows me to strive for excellence.

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Abstract

THE EFFECT OF DEPTH-OF-CURE ON THE FLEXURAL STRENGTH OF DENTAL BULK-FILL COMPOSITES

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Introduction: Newer bulk-fill composites claim to allow placement of 4 to 5mm increments with a full depth of cure **(DOC)**. Placing large single layered composites increases clinician speed and decreases technique sensitivity. To date, no studies consider how DOC affects the flexural strength of bulk-fill composites in specimens greater than 2mm of depth.

Objective: Investigate how the DOC influences the flexural strength and flexural modulus of 6 select resin-based composite (RBC) systems.

Methods: Six resin-based composite **(RBC)** systems tested: control-Filtek Supreme Ultra **(FSU)**, Filtek One Bulk **(F1B),** Tetric EvoCeram Bulk **(TECB),** Sonic Fill 3 **(SF3),** Surefill SDR plus **(SDR+)**, and Venus Bulk Fill **(VBF)**. Ten specimens of each composite type made with the width and length held constant and varying thicknesses (2mm, 3mm, 4mm, 5mm, and 6mm) totaling 300 specimens. Each specimen received 20 second exposure in the specimen center to 1241±5mW/cm^2 irradiances and then underwent 24 hours of dark cure in 37^o water bath. Specimen density values were measured using Archimedes method and then subjected to flexural strength testing using a universal testing machine. Data was analyzed by one-way ANOVA and post hoc Tukey's test (p=0.05).

Results: All bulk-fill RBCs experienced decreased flexural strength [MPa] as a function of specimen thickness except VBF which plotted similar values for both 2mm and 6mm specimens. F1B exhibited significantly higher flexural strength than all other RBC brands, for both, the 2 mm and 4 mm curing thicknesses. All RBC systems showed an inversely proportional trend between flexural modulus and specimen thickness. By in large, there is a linearly proportional relationship between RBCs' flexural strength and their density, as well as RBC's flexural modulus and their density.

Conclusion:
In general, flexural strength of bulk-fill RBCs decreases as material thickness increased with the largest decline in flexural strength observed at >4mm thickness. Flexural strength measurements and density measurements appear to be reliable methods to assess the physical DOC of different RBC systems. Some, but not all of the newest bulk fill composites, have physical properties equivalent or superior to the control, Filtek Supreme Ultra

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LIST OF ABBREVIATIONS

RBC----------- Resin Based Composite
FSU----------- Filtek Supreme Ultra
F1B----------- Filtek One Bulk
TECB-------- Tetric EvoCeram Bulk
SF3----------- Sonic Fill 3
SDR+-------- SDR Flow Plus
VBF---------- Venus Bulk Fill
DOC---------- Depth of Cure
SS------------- Stainless steel

Background

The purpose of a dental restoration is to replace the functional, esthetic, and biologic properties of healthy tooth structure.[1] Amalgam, being used for more than 150 years, has proven itself as a reliable means in restoring tooth structure. Nevertheless, amalgam, with its obvious esthetic short comings, is slowly being replaced by composite as the restorative material of choice in the United States and abroad.[2] Compared to amalgam, resin based composites are esthetically superior, more conservative and lacking the most controversial ingredient - mercury. Numerous organizations including the World Health Organization (WHO) affirm that mercury in dental amalgam poses no known systemic health concerns. However, continued controversy surrounding it as a health and environmental hazard has resulted in the WHO calling for a global amalgam "phase down" program.[3,4,5,7] This has influenced dental schools NYU college of Dentistry and South California School of dentistry to restrict its use. In addition to dental schools, countries such as Norway, Sweden, Denmark, Japan and Finland have also placed bans or restrictions against its use[3,5,6] The United States appears to be on the same amalgam free trajectory as these other countries. In November 2013, the United States joined in signing the Minamata Convention on Mercury which calls for a phase down of dental fillings using mercury amalgam.[8] Amalgam's shortcomings, combined with its controversy, have fueled intensive research by corporations and researchers in the field of composites.

Unfortunately, like amalgams, composites have unique draw backs which keep them from being the ideal restorative material. Composite resin restorations are more technique sensitive and time consuming.[9] Conventional RBC must be placed and cured in 2mm increments. Larger increments or inadequate curing can lead to bulk fractures, marginal breakdown, or recurrent caries. Layering has brought additional challenges such as increasing the probability of adding gaps between layers, potential cohesive failure between increments, the need to light cure each layer and the resultant shrinkage stress each layer may compound into the restoration. Additionally, layering makes restoring conservative preparations difficult and increases restoration placement time.[11,12,13] Filtek Supreme Ultra (FSU) is the most used conventional RBC in military dental treatment facilities. FSU, though a break-through when first introduced, is marketed to be placed in increments of no more than 2mm's.[14]

In order to address some of the above-mentioned limitations of conventional RBC, manufacturers have developed bulk-fill RBC systems that allow placement of 4 to 5mm increments with a full DOC. Placing these larger single layered composites has the potential to increase clinician speed and decreases technique sensitivity.[15] To achieve this, manufactures have employed a variety of strategies. Such strategies include increasing composite transparency, reducing monomer percentage through the addition of inorganic fillers, utilizing multiple-sized filler particles or prepolymerized filler particles, addition of low-shrinking monomers, and reducing the total number of covalent bonds formed.[16]

Many dental providers in the private sector have begun using bulk-fill resins almost exclusively for class II posterior composites. Other clinicians have been leery to change to a bulk-fill system, citing a lack of long-term clinical data available.[17] However, manufactures and proponents of bulk-fill RBCs contend that sufficient in-vitro research exists already. Campos et al concluded that there are no significant differences in marginal integrity, or microleakage between bulk-fill RBCs or conventional RBCs.[18] Perhaps most notable of all is an ADA report on a study that subjected 12 bulk-fill and conventional RBCs to a battery of tests. The conclusion was that the laboratory performance of the bulk-fill composites was comparable or better than the conventional multi-increment fill resins.[19]

The body of clinical evidence is also steadily growing. A one-year clinical evaluation concluded that the tested bulk-fill RBC materials showed similar clinical performance when compared to conventional RBCs.[20] A recently published 6-year randomized controlled clinical study compared a bulk-fill and conventional RBC in posterior restorations and concluded there was no significant difference in durability.[21] Furthermore, a 10-year randomized control trial comparing another bulk-fill RBC against a conventional RBC also showed no significant difference between the two materials. Both materials exhibited a high clinical effectiveness at the 10-year follow-up.[22] The present body of literature seems to validate the notion that bulk-fill materials are a suitable treatment modality for posterior restorations.

At the present date there are numerous recently developed bulk-fill RBC systems that have yet to be independently evaluated and compared via in vitro and in vivo investigations. Longitudinal studies are valuable in establishing the clinical serviceability of bulk-fill RBC systems. However, such study designs have several unique limitations. Materials researched in a 10-year RCT can be well antiquated before the research is complete. For example, Sonic Fill was introduced in 2011, then modified and released in 2015 as SonicFill 2 and then again modified in 2018 as SonicFill 3. A 10-year longitudinal study of Sonic Fill 1 loses some of its clinical significance when the material has become obsolete. Furthermore, the rate at which manufactures develop and evolve their products outpaces our capacity to perform longitudinal studies for each of them. For these reasons, continual in vitro testing of new composite systems is essential.

Flexural strength tests are commonly used to contrast the strength of different composite materials. Flexural strength is defined as the maximum bending stress that can be applied to a material before it yields. A high flexural strength is an important mechanical property for a bulk-fill resin. A systematic review of 31 different materials showed that flexural strength correlates moderately with clinical wear.[23] Ferracane et al proposed the 3-point bending test according to ISO 4049 as the standard test correlated with strength.[24]

The most useful and commonly cited tests to evaluate resin composites are the three and four-point bend tests, as outlined in ISO 4049.[23,25] From this test, flexural strength and modulus of elasticity can be determined. Materials with a high modulus of elasticity are considered stiff and those with lower values as flexible. An elastic modulus is a quantity that measures an object or substance's resistance to being deformed elastically (i.e., non-permanently) when a force/stress is applied to it. The modulus is calculated as the slope of the stress-strain curve in the elastic deformation region.

One of the most used methods to evaluate a materials depth of cure is via hardness testing. However, a good correlation was identified between indentation, and elastic modulus (three-point bending test).[26,27] Because of this correlation it is reasonable to suppose that flexural modulus can also be used to assess the physical DOC for RBC systems.

Prior research has examined flexural strength tests of bulk-fill composites and shown that bulk-fill composites having superior or equivalent flexural strengths as conventional composite resins.[28,29] To the best of the author's knowledge, no studies have examined how flexural strength or flexural modulus is affected when the composite samples are made greater than 2mm in depths. Since the clinical technique of bulk-fill consists of composite layers between 2-5mm, similar in vitro testing of flexural strength with varying depths may provide additional insight to the physical properties of bulk RBC systems. ISO 4049 provides guidance for testing flexural strength of 2mm depth composites but not for samples >2mm in depth. Our goal is to evaluate the differences in flexural strength and modulus of elasticity of different bulk-fill resin system with samples of varying depths from 2mm to 6mm via flexural strength testing. These results are then compared with our control Filtek Supreme Ultra, a conventional non-bulk-fill restorative material. The end purpose of these findings will hopefully assist clinicians in choosing the most suitable restorative materials to utilize in their clinical practice.

HYPOTHESIS:

The null hypothesis to be tested was there is no difference in flexural strength, or flexural modulus, between bulk-fill and conventional resin-based composites.

Materials and Methods

Measurements of flexural strength and flexural modulus:

The flexural strength and flexural modulus were determined in a three-point bending test. All samples were prepared in an orange lit room that lessened any unwarranted polymerizing effect of white ambient light on uncured composites. Five different rectangular stainless steel (SS) molds, having dimensions of 2x2x25, 2x3x25, 2x4x25, 2x5x25, and 2x6x25mm^3, were used to prepare a total of 300 specimens (See Figure 1).

To fabricate a rectangular specimen, a SS mold with one of the aforementioned dimensions was selected; it was then lightly lubricated with petroleum jelly (Vaseline, Unilever, London, United Kingdom) and placed on a plastic strip-covered glass slide. Next, a RBC was injected into the SS mold until it was filled. Then the top surface of the mold was covered with a second plastic strip and glass slide. A custom jig, consisted of three non-overlapping windows, was used to align three light guides for the delivery of adequate irradiance to the top surface. The three windows were linearly positioned such that they divided the 2X25mm^2 rectangular surface into three equal segments – each having equivalent irradiance area with one another. Using three light curing units of the same brand (1241+_5mW/Cm^2, Elipar FreeLight 2, 3M ESPE, St Paul, MN, USA), with one light guide per window, the three equally divided top rectangular surface was irradiated simultaneously. However, the specimen center received a duration of 20s light exposure, whereas the left and right sides to the specimen center received a duration of 40s light exposure (See Figure 2). The specimens were then removed from the mold and polished with silicon carbide paper (grit size P1200/4000, Buehler, Lake Bluff, IL, USA) (See Figure 3).Afterwards, they were stored in distilled water at an intraoral temperature of 37°C for 24 hours. (See Figure 4)

These aforementioned steps were repeated to fabricate a total of 50 samples per each of the six different resin based composite (RBC) brands: Filtek Supreme Ultra (FSU), Filtek One Bulk (F1B), Tetric EvoCeram Bulk (TECB), Sonic Fill 3 (SF3), Surefill SDR plus (SDR+), and Venus Bulk Fill (VBF) (See Figure 5). The control group was a conventional composite, FSU, while the experimental groups were F1B, TECB, SF3, SDR+, and VBF, which were categorized by their respective manufacturers as bulk-fill composites. A "gold standard" integrating sphere fitted with a photo-spectrometer was used to verify the irradiance output and consistency of the three light curing units.

Subsequently, each specimen was placed on a 3-point bending test apparatus which was constructed with a 20 mm span length between the supporting rods (See Figure 6). A central load was applied with a head diameter of 2mm, and a crosshead speed of 0.5mm/min using a universal testing machine (Instron, Norwood, MA, USA). The flexural strength was calculated using the equation:

$$\sigma = \frac{3Fl}{2bd^2}$$

Where F is the loading force at the fracture point, *l* is the length of the support span (20 mm), b is the width, and d is the depth. Measurements were made using an electronic digital caliper (SPI 13-610-1, Swiss Precision Instruments, Melville, NY, USA) (See Figure 7). Flexural modulus will be determined from the slope of the linear region of the load-deflection curve using analytical software (Instron, Norwood, MA, USA).

Density measurements:

Prior to the three-point bending test, the density of each rectangular specimen was calculated using the buoyancy or Archimedes method.[30] Because the buoyant force experienced by a submerged object is equal to the weight of the liquid displaced by the object, the density of that object can therefore be calculated based on the difference amongst the object mass in air (or dry mass, m_{dry}), the object mass when immersed in liquid (or wet mass, m_{wet}), and the density of the liquid (ρ_{liquid}). Thus, the RBC density (ρ_{RBC}) can be determined from the following equation:

$$\rho_{RBC} = \frac{m_{dry}}{m_{dry} - m_{wet}} \rho_{liquid}$$

In this study, ρ_{liquid} is the density of water at room temperature, 25.5°C. The dry and wet masses of each specimen were measured using an analytical balance fitted with a density measurement kit (AGCN200, Torbal, Bohemia, NY) (See Figure 8).

Statistical Analysis:

Data was analyzed by one-way ANOVA and post hoc Tukey's test (p=0.05). A Non-linear regression was used to fit the correlation between thickness and flexural strength and a linear regression used to correlate thickness verses modulus. An analysis of variance was performed with p<0.0001.

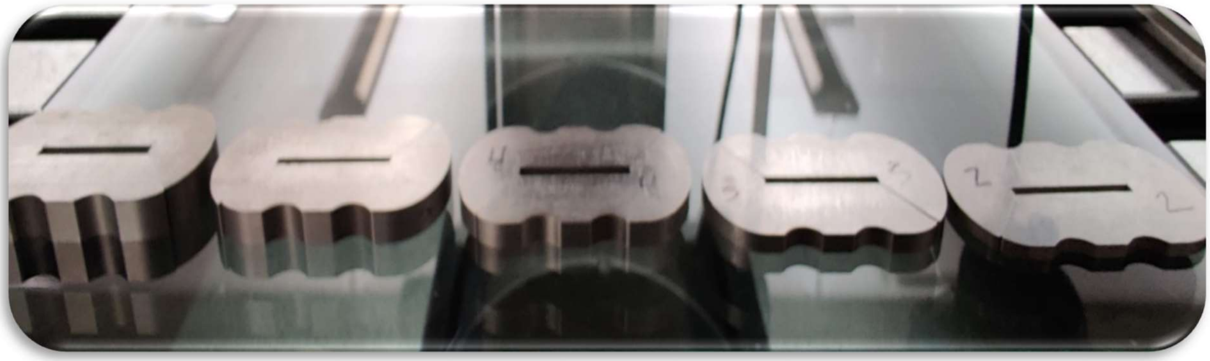


Figure 1. Flexural strength jigs used to make composite samples varying only in depth. From right to left; 2mm, 3mm, 4mm, 5mm, and 6mm jigs.

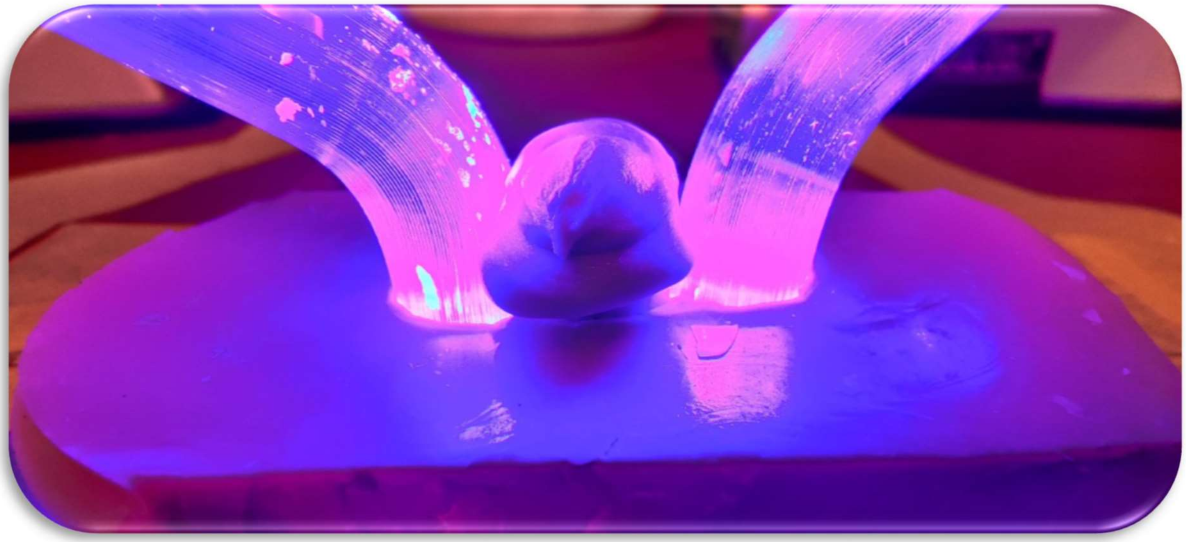


Figure 2. Specimen prepared in an orange ambient lighted room and photopolymerized with the Elipar FreeLight 2

Figure 3. Specimen ground with silicon carbide paper to remove protruding edges.

Figure 4. Specimens stored in distilled water at room temperature prior to flexural testing

Figure 5. Six RBCs tested from left to right: FSU- Filtek Supreme Ultra, F1B- Filtek One Bulk, TECB- Tetric EvoCeram Bulk Fill, SF3- Sonic Fill 3, VBF- Venus Bulk Fill, & SDR+- Surefill SDR flow plus.

Figure 6. Specimen subjected to flexural strength testing using the Instron universal testing machine

Figure 7. Digital calipers used to measure variations in sample depth after sanding edges.

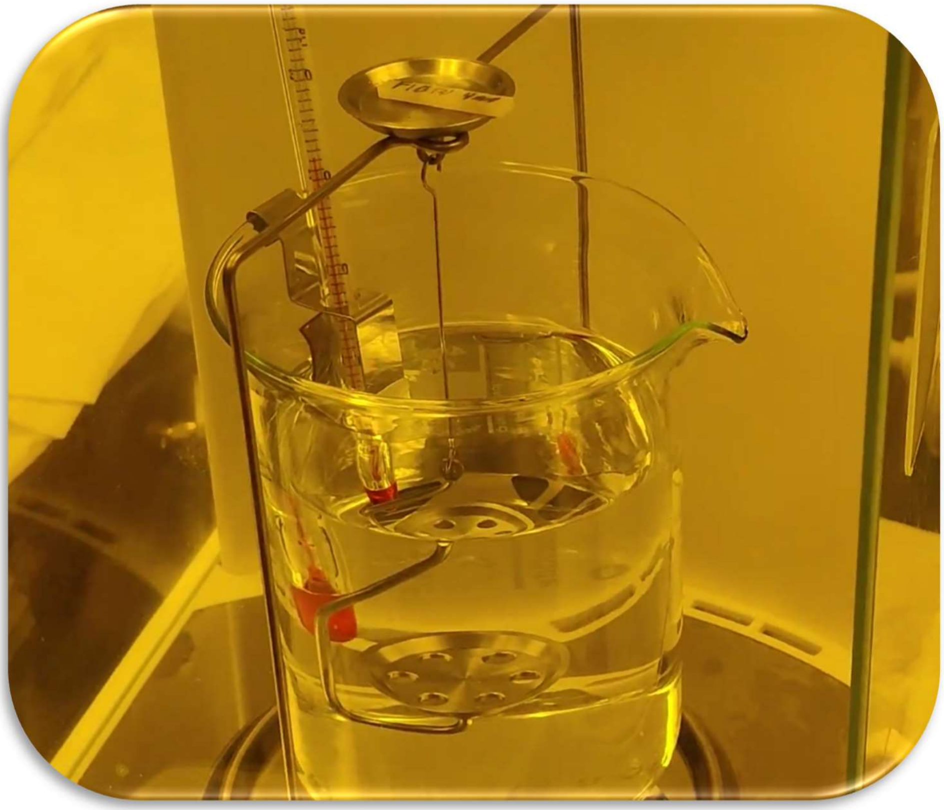


Figure 8. Specimen density recorded using a Torbal scale and Archimedes method.

Results

Flexural strength

Generally, the flexural strength of the RBCs decreased with increasing thickness of the prepared sample. The highest flexural strength value recorded was for the F1B 2mm samples with a mean of 171 MPa and 4mm mean of 165.10 MPa. The lowest recorded values were seen with SF3 and TECB (See Figures 9 and 11). Three RBC systems (FSU, SF3 and TECB) showed decreasing flexural strength with increasing sample thickness. Two bulk-fill RBCs (FIB, SDR+) had almost unchanged flexural strength values independent of sample depths from 2mm to 5mm. F1B had a sharp decrease in flexural strength between 5mm and 6mm samples. Surprisingly, VBF, was the only RBC system that showed greater flexural strength values as sample thickness was increased (See Figure 9 and 11). Flexural strength values in the 2mm and 4mm sample depths were similar for FSU, SDR+ and VBF.

Flexural modulus

Regardless of RBCs tested, all showed an inversely proportional trend between flexural modulus and specimen thickness. F1B and FSU had the highest flexural modulus values approximating 13000 MPa in the 2mm sample range and a 6mm depth samples having a drastic reduction to 4000 MPa. VBF had the overall lowest flexural modulus values followed by SDR+ (See Figure 11).

Flexural strength & modulus as a function of density

All RBCs exhibited a linearly proportional relationship between their flexural strength and their density as well as between their flexural modulus and density. Generally, all samples tested showed 2mm samples being the densest and gradually declining in density with increasing sample thickness. TECB had the highest overall density among all RBC systems tested and SF3 had the lowest (See Figure 12). F1B, FSU, SF3, and TECB exhibited more than 70% reduction in flexural modulus as the specimen thicknesses were increased from 2mm to 6mm.

Figure 9: Flexural strength [MPa] as a function of specimen thickness for various bulk-fill resin-based composites is plotted for comparison. Each specimen underwent 24 hours of dark cure in 37 ºC water bath, after 20 s exposure in the specimen center to 2031 ± 5 mW/cm^2 irradiances. Each data set is fitted using a sigmoidal function, where *S* is the flexural strength; *x* is the specimen thickness; and *a*, *b*, and x_o are fitting constants. Here, to eliminate the effects of how various specimen thicknesses can interfere with load comparison, each flexural load value is normalized to a flexural strength value.

The sigmoidal function is: $S = \frac{a}{1+e^{\frac{-(x-x_O)}{b}}}$

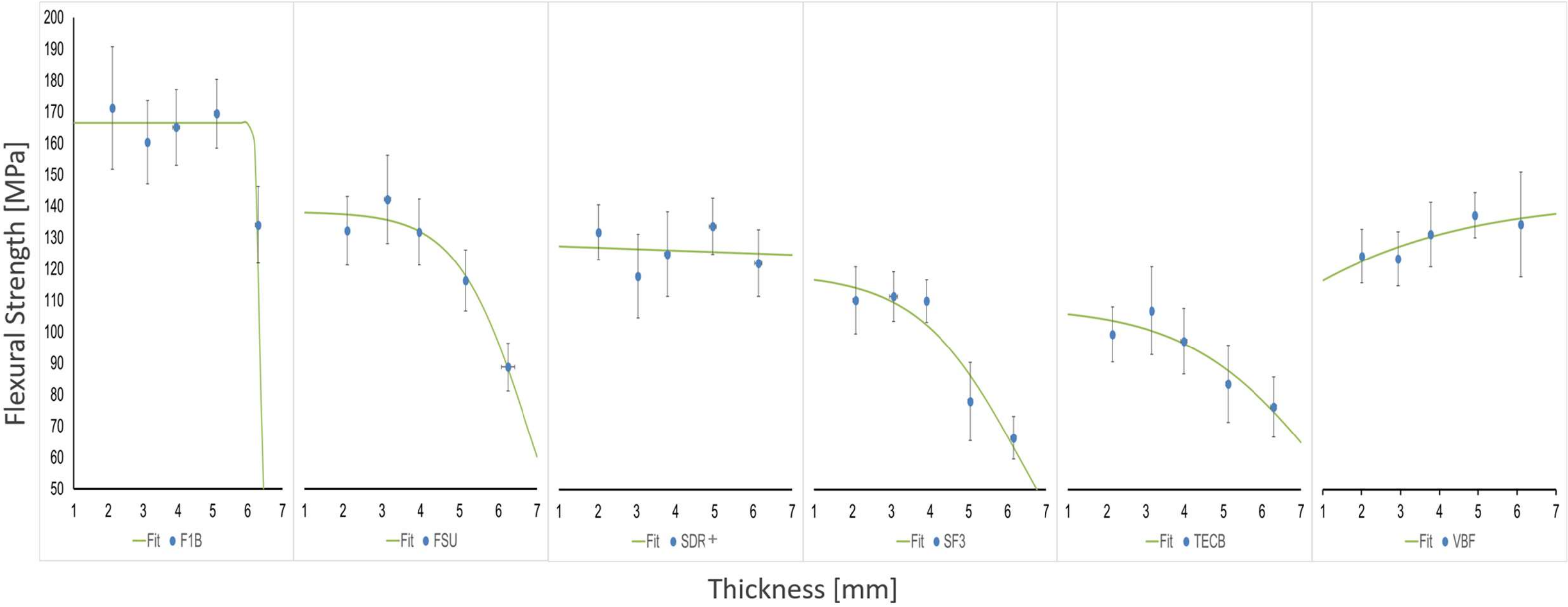


Figure 10: Flexural modulus [MPa] as a function of specimen thickness for various bulk-fill resin-based composites is plotted for comparison. Each specimen underwent 24 hours of dark cure in 37 ºC water bath, after 20 s exposure in the specimen center to 2031 ± 5 mW/cm^2 irradiances. Each data set is linearly fitted to show inversely proportional trend between flexural modulus and specimen thickness.

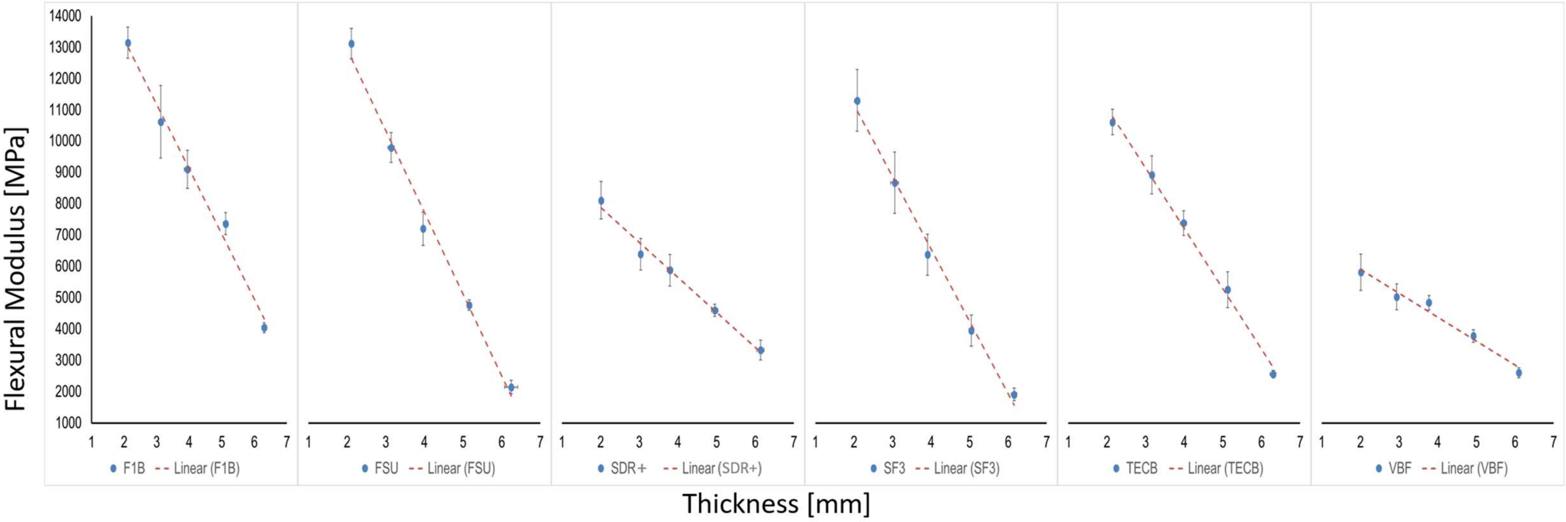


Figure 11: The flexural strength of various bulk-fill resin-based composites are plotted. The thickness of each resin-based composite sample for which curing light traverses was either 2 mm or 4 mm thick. Specimen width and length were kept constant. Each specimen underwent 24 hours of dark cure in 37 ºC water bath, after 20 s exposure in the specimen center to 2031 ± 5 mW/cm^2 irradiances. The same case letters across columns are not significantly different than each other ($p > 0.05$). F1B exhibited significantly higher flexural strength than all other RBC brands, for both, the 2 mm and 4 mm curing thicknesses.

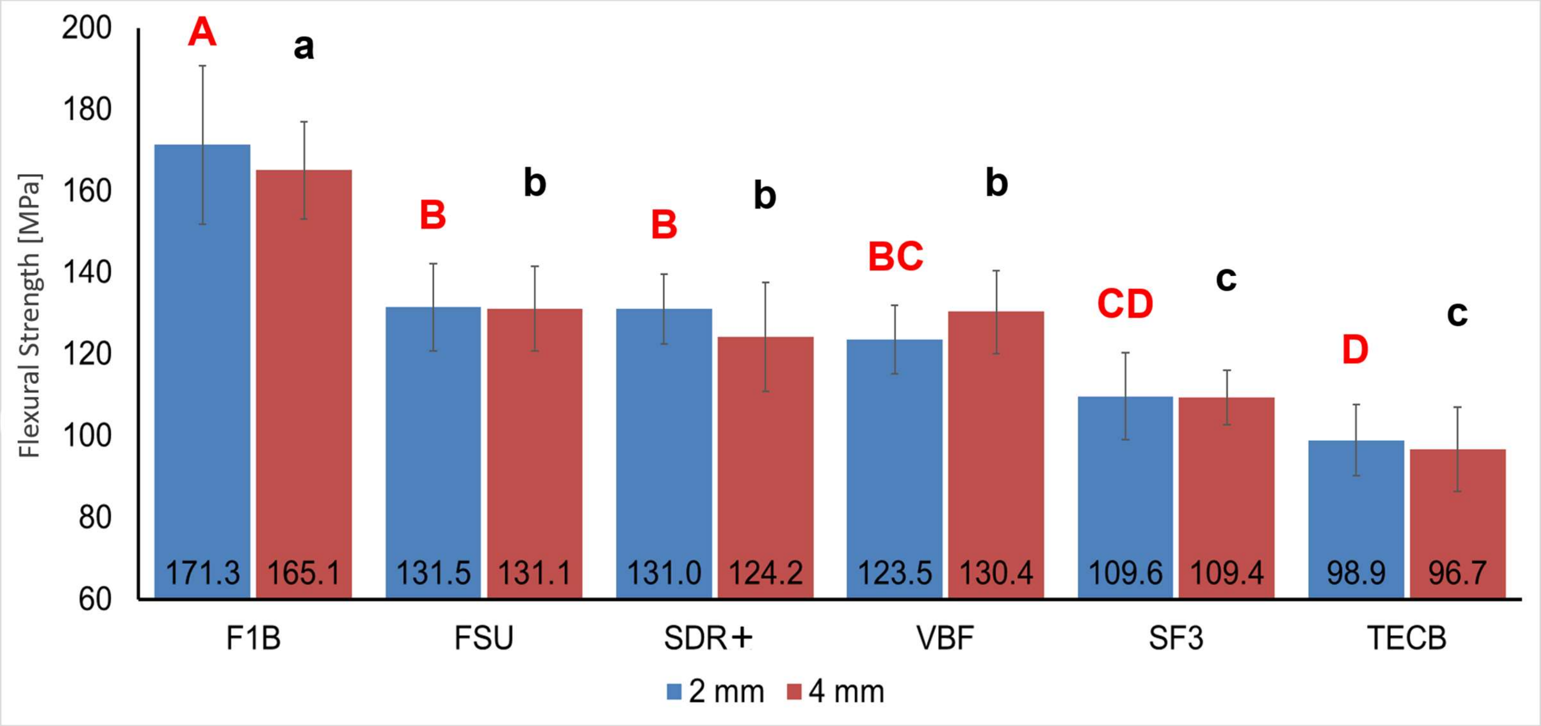


Figure 12: Both, flexural strength [MPa] and flexural modulus [MPa] as a function of density [g/cm^3], are plotted. Each specimen underwent 24 hours of dark cure in 37 ºC water bath, after 20 s exposure in the specimen center to 2031 ± 5 mW/cm^2 irradiances. In general, there is a linearly proportional relationship between RBCs' flexural strength and their density, as well as RBC's flexural modulus and their density. The density values were measured using Archimedes principle. F1B, FSU, SF3, and TECB exhibited more than 70% reduction in flexural modulus as the specimen thicknesses were increased from 2 mm to 6 mm, signifying inadequate cure at those distances that are greatest away from the curing source.

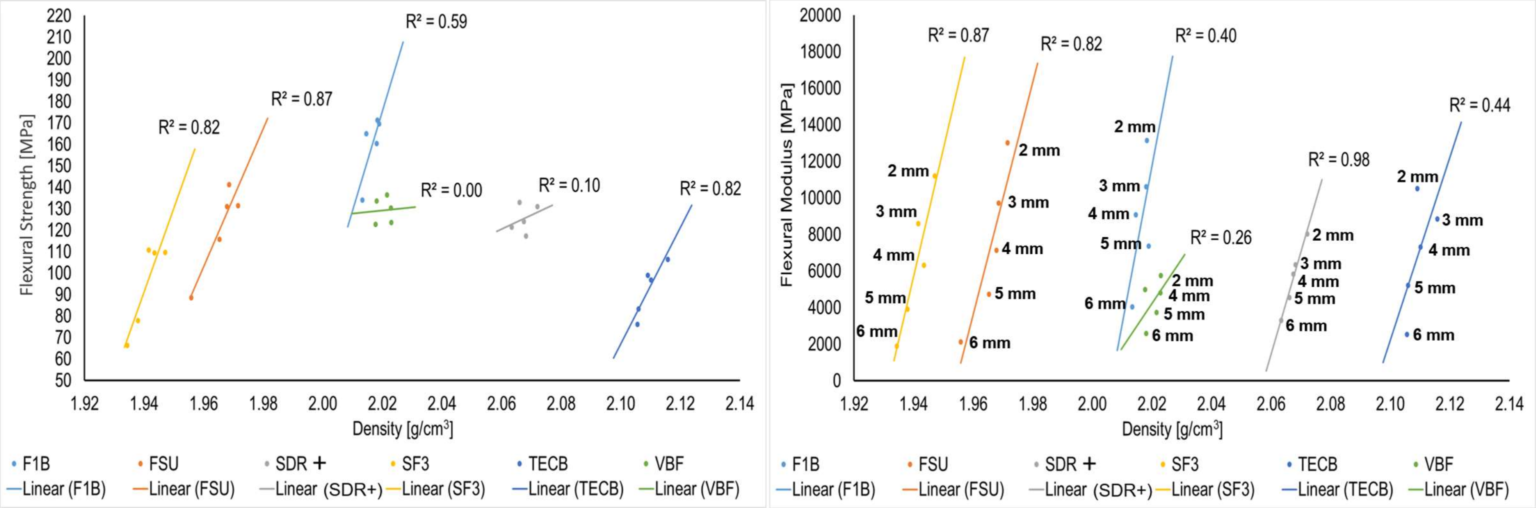
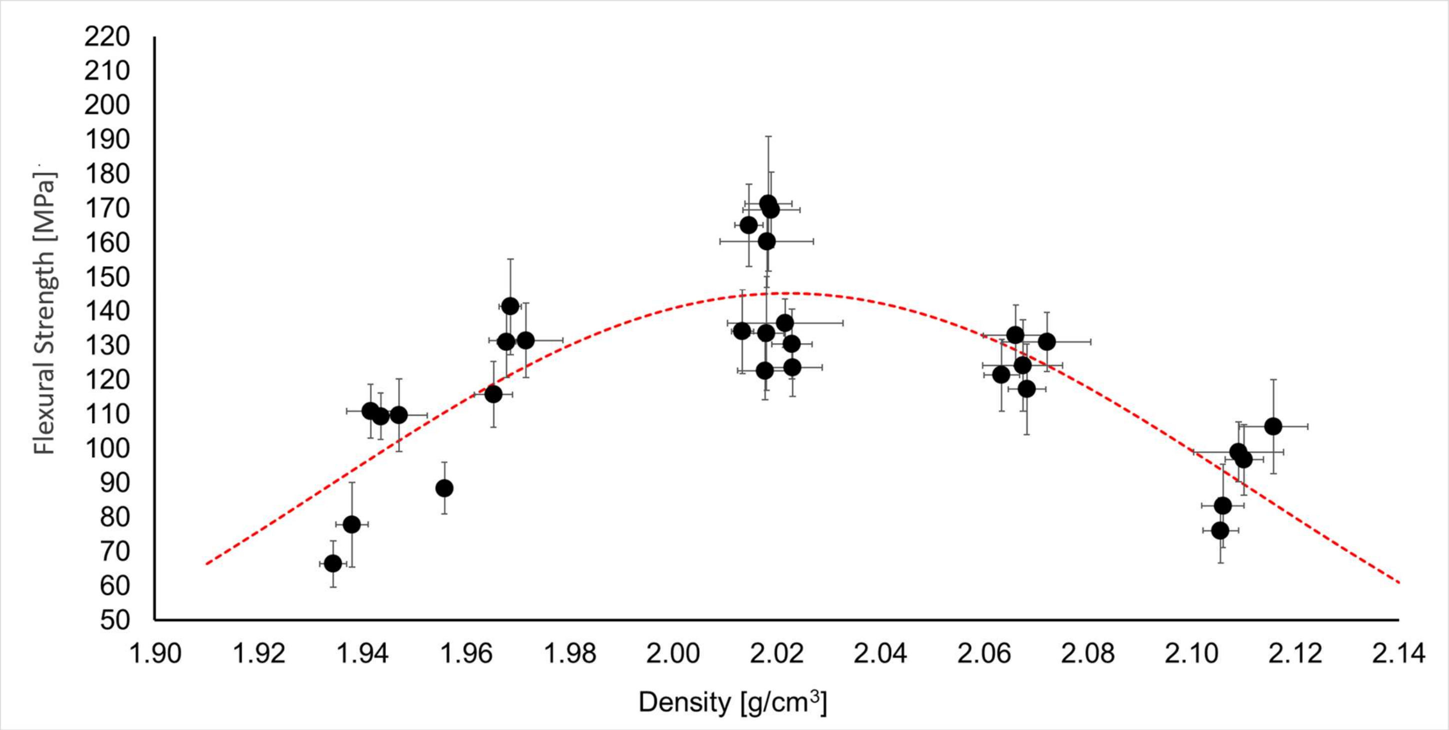


Figure 13: In general and irrespective of RBC brands, when flexural strength as a function of density is plotted, there exists an optimal value, sweet spot, at which the density maximizes the material's flexural strength. The red dotted line represents the fitted curved assuming the correlation between flexural strength and density is Gaussian function.



Discussion

This study evaluated the flexural strength and flexural modulus of five bulk-fill RBC systems with specimens of various depths. Results were compared against a conventional RBC. Significant differences in flexural strength were observed between a few of the bulk-fill RBCs and the control, which led to the rejection of the null hypothesis.

In general, flexural strength for bulk-fill RBCs decreased as material thickness increased, with the largest decline in flexural strength observed at >4mm of DOC (See Figure 9). Most materials perform optimally when placed in smaller increments. Nevertheless, as Figure 11 demonstrates, the flexural strength difference between 2mm and 4mm depths of similar composites is small and perhaps clinically insignificant. The precipitous drop in flexural strength after 4mm further supports maintaining no more than 4mm composite increments in most materials. However, the same results indicate that materials such as F1B can support a DOC of 5mm along with SDR+, and VBF with a greater >5mm DOC. Results also highlight that not all bulk-fill RBC systems are created equal. Surprisingly SF3 and TECB, two popular bulk-fill RBCs, had average flexural strength values lower than the control in every sample thickness tested. This difference could indicate inferior physical properties of SF3 and TECB and highlight the exceptional properties of FSU and F1B, the only true nanofill RBCs tested. Another differing conclusion may point to a limitation of the present study. TECB has a unique photo initiator system. The light source used in this study is a monophase light. To fully cure TECB it may be necessary to use a polyphase light such as the bluephase style light that is recommended by Ivoclar Vivadent. Research shows that that Lucirin and Ivocerin are more efficient photoinitiators than camphorquinone.[31,32] To better assess the influence of Lucirin and Ivocerin in composites, the present study should be repeated using a polyphase light source.

Also, important when comparing the study results is to acknowledge that most systems have differing photopolymerization instructions regarding light intensities and curing times. For example, Sonic Fill 3 advertises a 5mm DOC and directs clinicians to photopolymerize all posterior restorations with a LED light output >1000 mW/cm2. The manufacture further explains that 10 sec polymerizations from the occlusal, buccal, and lingual surfaces are needed for a total of 30 seconds. This method of photopolymerizing was not possible in the present study because steel molds were used instead of extracted teeth. In contrast to SF3, SDR+ advises one surface photopolymerization with a light of 550-1000mW/cm^2 for 20 seconds with its universal shade. See table 1 for a breakdown of some of the main differences and similarities between the tested composite systems to include shade types.

The property of translucency seems to be the most important factor enabling a material to have a deep DOC. This is supported by the fact that SDR+ and VBF, the most translucent RBCs tested, showed the most stable flexural strength values and flexural modulus values from 2-6mm (See Figures 9 and 10). One of the ways manufactures produce a more translucent restorative material is by reducing the amount of inorganic filler. From table 1 we note that SDR+ and VBF have the lowest filler content of the six composites tested. Having a large DOC by decreasing filler content does come with consequences. As manufactures replace inorganic fillers with more monomers, the RBC decreases in strength, increases its polymerization shrinkage, and becomes more translucent. A translucent posterior restoration may be acceptable, but many clinicians find them too unaesthetic for anterior fillings. A universal shade, which is substantially more translucent than A2, was used in this study for SDR+ and VBF. All the other RBC systems were shade A2. The shade differences between the systems makes a side by side comparisons more complicated. However, considering that the only shade available for VBF is universal and is also the most used for SDR+, the use of universal shade in the present study can be justified.

Ample scientific literature supports the use of ISO 4049 scrape test and or hardness tests to evaluate a materials DOC. The present study demonstrates that two other methods, not well documented in the scientific literature are also feasible in evaluating a materials DOC. Though more time consuming to perform than the prior listed methods, flexural testing appears to correlate with DOC. Additionally, measuring a composites polymerized density via the Archimedies method also correlates with DOC (See Figure 12).

Perhaps one of the most interesting findings of this study relates to the correlation between density and flexural strength. When flexural strength as a function of density is plotted irrespective of RBC brands, there exists an optimal value or sweet spot, at which the density maximizes the materials flexural strength (See Figure 13). In other words, materials with polymerized densities closest to 2.02 g/cm^3 tend to have superior physical properties than those denser than 2.02 g/cm^3 or less dense. Future studies should be performed with more RBC systems to see if this optimal density value holds true.

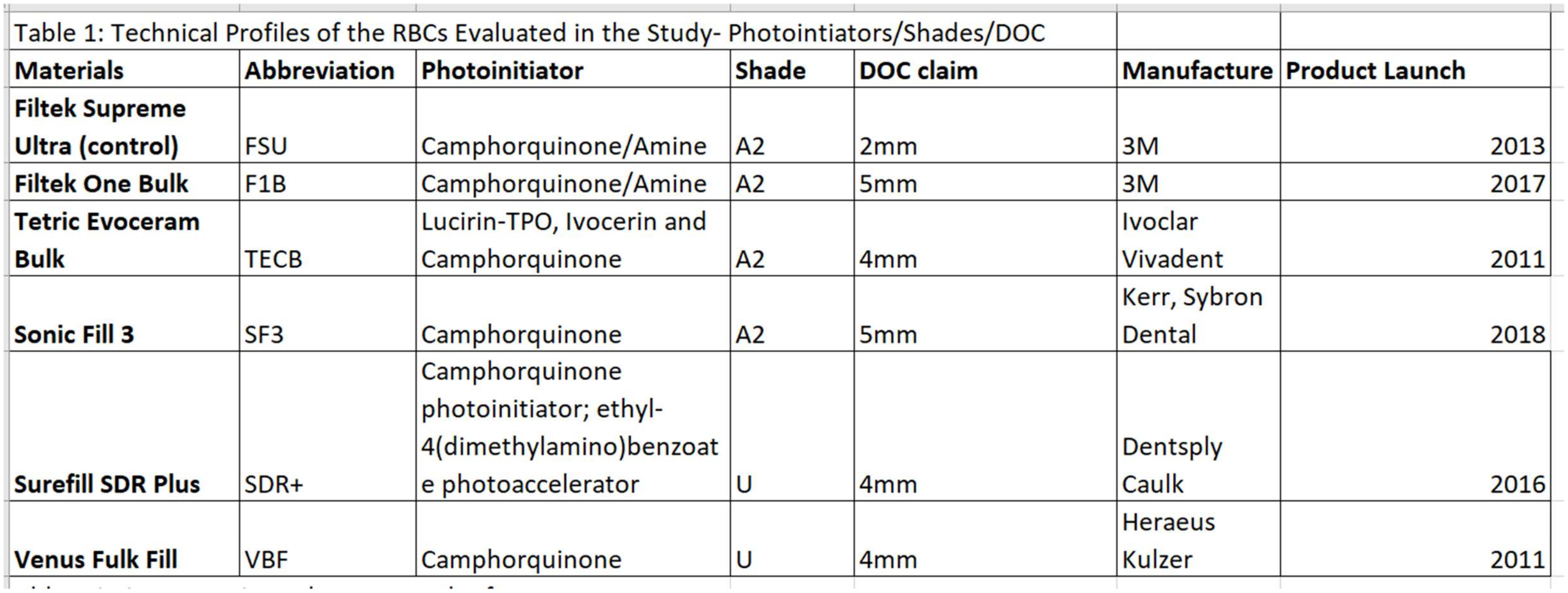


Table 1: Technical Profiles of the RBCs Evaluated in the Study- Photointiators/Shades/DOC

Materials	**Abbreviation**	**Photoinitiator**	**Shade**	**DOC claim**	**Manufacture**	**Product Launch**
Filtek Supreme Ultra (control)	FSU	Camphorquinone/Amine	A2	2mm	3M	2013
Filtek One Bulk	F1B	Camphorquinone/Amine	A2	5mm	3M	2017
Tetric Evoceram Bulk	TECB	Lucirin-TPO, Ivocerin and Camphorquinone	A2	4mm	Ivoclar Vivadent	2011
Sonic Fill 3	SF3	Camphorquinone	A2	5mm	Kerr, Sybron Dental	2018
Surefill SDR Plus	SDR+	Camphorquinone photoinitiator; ethyl-4(dimethylamino)benzoate photoaccelerator	U	4mm	Dentsply Caulk	2016
Venus Fulk Fill	VBF	Camphorquinone	U	4mm	Heraeus Kulzer	2011

Abbreviation: U, Universal; DOC, Depth of Cure
Unless otherwise stated, all information list is from manufacturer data.

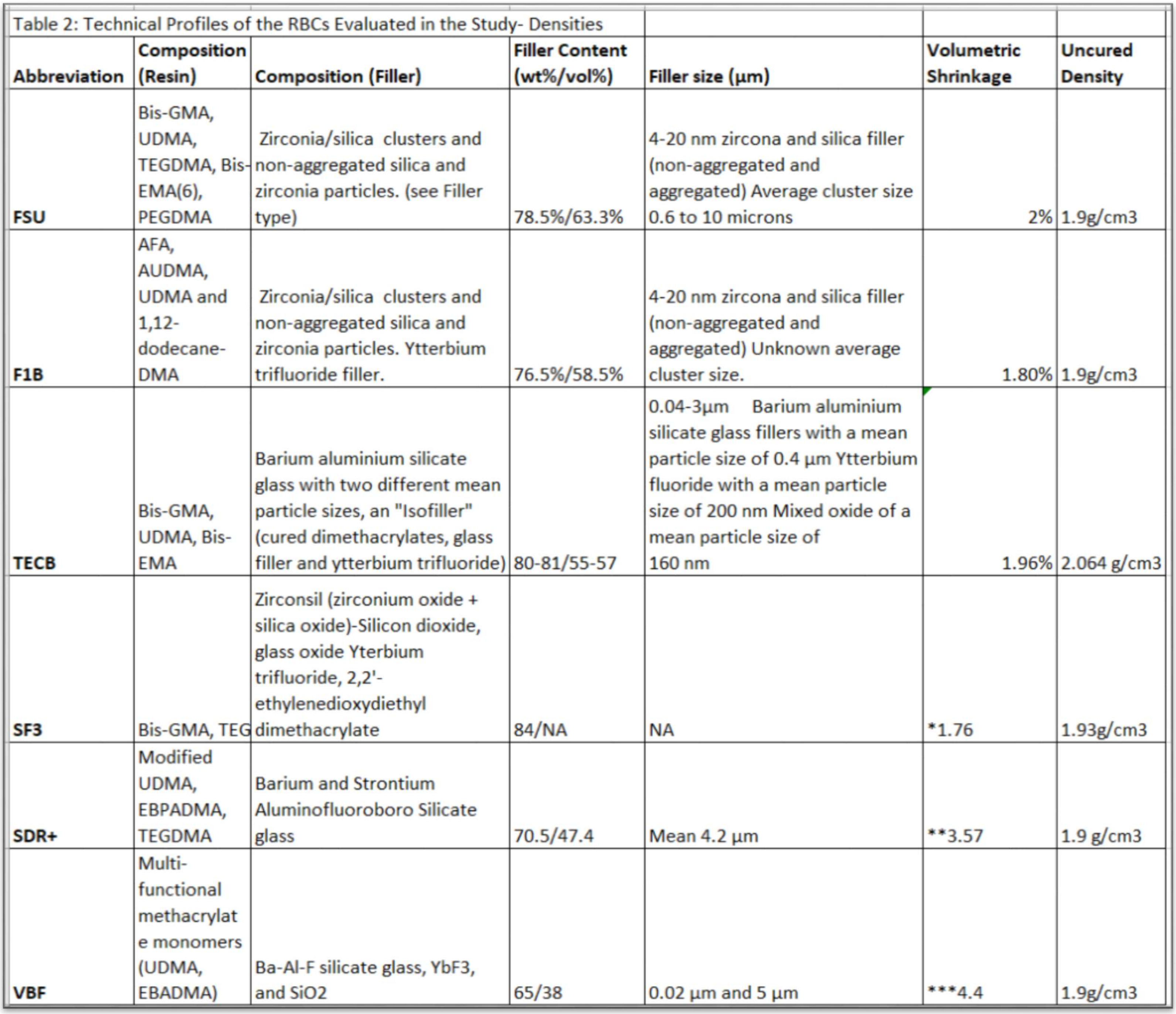


Table 2: Technical Profiles of the RBCs Evaluated in the Study- Densities

Abbreviation	Composition (Resin)	Composition (Filler)	Filler Content (wt%/vol%)	Filler size (µm)	Volumetric Shrinkage	Uncured Density
FSU	Bis-GMA, UDMA, TEGDMA, Bis-EMA(6), PEGDMA	Zirconia/silica clusters and non-aggregated silica and zirconia particles. (see Filler type)	78.5%/63.3%	4-20 nm zircona and silica filler (non-aggregated and aggregated) Average cluster size 0.6 to 10 microns	2%	1.9g/cm3
F1B	AFA, AUDMA, UDMA and 1,12-dodecane-DMA	Zirconia/silica clusters and non-aggregated silica and zirconia particles. Ytterbium trifluoride filler.	76.5%/58.5%	4-20 nm zircona and silica filler (non-aggregated and aggregated) Unknown average cluster size.	1.80%	1.9g/cm3
TECB	Bis-GMA, UDMA, Bis-EMA	Barium aluminium silicate glass with two different mean particle sizes, an "Isofiller" (cured dimethacrylates, glass filler and ytterbium trifluoride)	80-81/55-57	0.04-3µm Barium aluminium silicate glass fillers with a mean particle size of 0.4 µm Ytterbium fluoride with a mean particle size of 200 nm Mixed oxide of a mean particle size of 160 nm	1.96%	2.064 g/cm3
SF3	Bis-GMA, TEG	Zirconsil (zirconium oxide + silica oxide)-Silicon dioxide, glass oxide Yterbium trifluoride, 2,2'-ethylenedioxydiethyl dimethacrylate	84/NA	NA	*1.76	1.93g/cm3
SDR+	Modified UDMA, EBPADMA, TEGDMA	Barium and Strontium Aluminofluoroboro Silicate glass	70.5/47.4	Mean 4.2 µm	**3.57	1.9 g/cm3
VBF	Multi-functional methacrylate monomers (UDMA, EBADMA)	Ba-Al-F silicate glass, YbF3, and SiO2	65/38	0.02 µm and 5 µm	***4.4	1.9g/cm3

Abbreviation: Bis-GMA, bisphenol A glycidyl dimethacrylate; Bis-MPEPP, 2,2-bis[(4-methacryloxy polyethoxy)phenyl)propane; EBPADMA, ethoxylated bisphenol A dimethacrylate; NA, not available; S-PRG: surface pre-reacted glass ionomer; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate; Bis-EMA(6), Bisphenl A polyethylene glycol diether dimethacrylate, EBADMA: ethoxylated Bis-GMA

Unless otherwise stated, all information listed is from manufacturer data and SDS sheets.

*NA for SF3- Data used from original SF

** NA for SDR+- Data used for original SDR flow

***Garcia, D., et al. "Polymerization shrinkage and depth of cure of bulk fill flowable composite resins." Operative dentistry 39.4 (2014): 441-448.

Conclusion

Scrape and hardness testing are well established methods for determining DOC of RBC systems. Flexural strength and density testing of samples varying in thickness also appear to be reliable methods to establish DOC. However, the fabrication of multiple flexural strength samples is relatively time intensive as compared to the more practical scrape and hardness testing for DOC assessment.

Of the 4 high viscosity RBC systems F1B exhibited the highest flexural strength. Of the two low viscosity bulk fills, VBF revealed the highest flexural strength. Both F1B and VBF possess densities closest to 2.02g/cm^3. RBC systems with polymerized densities closest to 2.02 g/cm^3 appear to maximize the materials flexural strength as compared to those with densities more or less than 2.02 g/cm^3.

Of the 6 RBC systems tested, all had comparable flexural strengths at 2mm compared to 4mm DOC. This signifies that all tested composites can be used as bulk fills. However, two RBC systems (TECB & SF3) had significantly lower flexural strengths when compared to the remaining four (F1B, FSU, SDR+, VBF).

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