Published in final edited form as:

Dent Mater. 2010 March ; 26(3): 207. doi:10.1016/j.dental.2009.10.002.

Cyclic loading of notched dental composite specimens

Lihong Lin and James L. Drummond*

Department of Restorative Dentistry, University of Illinois at Chicago, Chicago, Illinois USA

Abstract

Objective—The purpose of this study was to examine the fracture toughness (K_{IC}) of three direct dental composites and one indirect dental composite subject to cyclic loading.

Methods—The composites were a micro-filled (Micronew, Bisco INC., Schaumburg, IL, USA), a hybrid (Renew, Bisco INC.), a nano-filled composite (Filtek Supreme Plus, 3M ESPE, St. Paul, MN, USA) and an indirect dental composite (BelleGlass HP, SDS-Kerr, Orange, CA, USA). Rectangular bar specimens (3mm x 3mm x 25 mm) were fabricated, notched, aged (five months) and cyclic loaded in four different environments, air, water, artificial saliva, and a 50/50 by volume mixture of ethanol and water. Specimens were cyclic loaded for 1, 1,000, 10,000, and 100,000 cycles.

Results—A three-way ANOVA (non-aged and aged group, four aging media, four loading cycles) showed a significant difference between non-aged and aged, aging media, and loading cycles. For the control groups as the number of cycles increased, there were no significant differences on the number of cycles completed and fracture toughness, except for Micronew, which showed an increased specimen failure rate and decreased fracture toughness. In the aged groups, cyclic loading in water and artificial saliva did not have a significant effect on BelleGlass HP, Filtek Supreme Plus and Renew for fracture toughness and the number of cycles completed. However for Renew in the 50/50 mixture at 100,000 cycles, Filtek Supreme Plus in air and the 50/50 mixture, and Micronew, there was an increased specimen failure rate and a decreased fracture toughness during cyclic fatigue loading as the number of cycles increased.

Significance—BelleGlass HP displayed the best overall resistance to cyclic loading, followed by Renew and Filtek Supreme Plus, and Micronew.

Keywords

dental composites; cyclic loading; aging; fracture toughness

Introduction

The application of resin based restorative dental composite materials in mastication-load-bearing areas is a concern since failure occurs frequently due to marginal fracture, bulk fracture, and/or wear [1,2]. These materials are subjected to mastication forces that are low and repetitive (fatigue) with the concern that the reported fatigue behavior of resin composites does not correlate with initial strength values, and materials providing high initial strengths may not reveal the best fatigue resistance [3,4].

*Corresponding author: James L. Drummond, DDS, PhD, 350 College of Dentistry, Department of Restorative Dentistry m/c 555, 801 South Paulina Street, University of Illinois at Chicago 60612-7212, Phone 312-996-2669; Fax 312-996-3535; drummond@uic.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Restorative dental materials are classified as direct and indirect dental materials depending on how processed. Direct restorative dental materials are utilized directly in the intraoral environment; whereas, indirect restorative dental materials are laboratory-processed materials, such as inlays or onlays. Several studies have reported increased mechanical properties of indirect composite compared to direct composite resulting from a post-cure treatment or second polymerization cycle [5,6]. The increased mechanical properties of indirect dental composites resulted from the increased degree of cure (DC) of monomers which contribute to toughening of the filled resin matrix and possibly an improved filler/matrix adhesion, and the relief of internal stresses by the high temperature treatment. Other studies have indicated that indirect composites are not superior compared to direct composite [7] and that post curing resulted in moderate improvement (~9%) of selected mechanical properties [8].

In most instances, stress applied to teeth and dental restorations is generally low in value and repetitive (fatigue) rather than being a single, impact load [9]. The normal occlusal loading of a filling is estimated at between 5 and 20 MPa [10] and occasionally, a higher peak stress may occur during parafunctional movement, such as during maximum clenching increasing to 100 MPa [11].

The purpose of this study was to examine the fracture toughness (K_{IC}) resistance to cyclic loading of three direct dental composites, a micro-filled (Micronew, Bisco INC., Schaumburg, IL, USA), a hybrid (Renew, Bisco INC., Schaumburg, IL, USA), a nano-filled composite (Filtek Supreme Plus, 3M ESPE, St. Paul, MN, USA) and an indirect dental composite (BelleGlass HP, SDS-Kerr, Orange, CA, USA), after aging and cyclic loading fatigue in four different environments, air, water, artificial saliva, and a 50/50 by volume mixture of ethanol and water.

Materials and Methods

Four dental composites were included in this study; three direct dental composites micro-filled Micronew, hybrid Renew, nano-filled Filtek Supreme Plus, and the indirect dental composite, BelleGlass HP.

The bar dimensions and testing methodology for fracture toughness were according to ASTM Standard PS070-097 [12]. Rectangular bar specimens (3mm × 3mm × 25 mm) were fabricated using a Plexiglas split mold so that no force was required to remove the cured bars. The split mold was placed on a Plexiglas slab lined with a piece of Mylar strip. Uncured composite was inserted into the mold and then a second Mylar strip was used to cover the uncured composite. A second Plexiglas slab was placed on the top, clamps used to stabilize the split mold, and the entire Plexiglas mold assembly cured in an oven (Triad, Dentsply/York Division, Dentsply International, York, PA, USA) for 2 minutes on each side. Specimens were then hand-polished with 320 grit SiC paper.

The same method was used to fabricate the indirect composite specimens except a metal split mold was used instead of a Plexiglas split mold. The entire metal mold assembly was cured in an oven (Triad, Dentsply/York Division, Dentsply International, York, PA, USA) for 2 minutes with the open slot side of the mold upward for the first step photo polymerization. Then the assembly was placed into a BelleGlass HP curing unit (SDS-Kerr) for the second step, pressure and heat polymerization under 140°C and 80 psi nitrogen. Specimens were then hand-polished with 320 grit SiC paper.

A 60 degree notch was machined 0.75 mm deep at the midspan of each bar except for Micronew, which had 1.00 mm deep notch. A 1.00 mm notch was chosen for Micronew as a continuation of a previous study, that used a fiber reinforced dental composite, which has high flexure strength [4]. Only after the Micronew samples were prepared was it realized that

Micronew was very weak, and a 0.75mm notch later on was decided to be used for the other specimens. Theoretically, the value of fracture toughness is not influenced by notch size since it was calculated by the formula described below, which takes notch size into consideration. Specimens were aged at 37°C for five months in air or 200 ml of artificial saliva or water or a 50/50 by volume mixture of ethanol and water. Composition of the artificial saliva used in this study was in g/L 0.4 NaCl, 0.795 CaCl₂·2H₂O, 0.78 NaH₂PO₄·2H₂O, 0.005 Na₂S₂O₈·9H₂O, 1.0 CO(NH₂)₂.

Both control and aging group specimens were loaded in each corresponding media at a frequency of 5 Hz with sinusoidal loads cycling between 5 N and 10 N for 1, 1,000, 10,000 and 100,000 cycles on a 858 Mini Bionix II testing device (MTS Systems Corporation, Minneapolis, MN). The load limit was chosen to be approximately 40–50% of the static loaded specimens and a stress level normally encountered during mastication. Following cyclic loading, the intact specimens were tested in three-point loading in their respective media using a Instron 1125 (Instron Corp., Canton MA) material testing system controlled by MTS (MTS Systems Corporation, Minneapolis, MN) digital electronics with a loading speed of 2 mm/min. For every specimen that fractured during cyclic loading, and thus could not be tested in three-point loading, the K_{IC} value was set to zero. The number of cycles for each specimen, fractured and intact, was recorded.

Fracture Toughness K_{IC} was computed from a standard fracture mechanics formula [12]:

$$K_{IC} = \frac{PLf_1(a)}{BH^{1.5}} \quad \text{where } a = a_0/H, \text{ and} \\ f_1 = \frac{3a^{0.5} [1.99 - a(1-a)(2.15 - 3.93a + 2.7a^2)]}{2(1+2a)(1-a)^{1.5}}$$

P is the measured load at specimen fracture, L is the support span, B is the specimen thickness, H is the specimen height, and a_0 is the notch depth.

The statistical analysis consisted of four 2-way ANOVAs followed by Tukey's HSD inference, and two 3-way ANOVAs followed by two-sample *t*-tests. This study included two dependent variables and four independent variables. The two dependent variables were the average number of cycles completed and the fracture toughness of the composite and the four independent variables were: composites (Micronew, Renew, Filtek Supreme Plus, and BelleGlass HP); aging (control (no aging) and aged (five months aging)); media (air, water, artificial saliva and 50/50 by volume mixture of ethanol and distilled water); and number of cycles (1, 1,000, 10,000, and 100,000). The data were analyzed first in terms of the average number of cycles completed, and then in terms of the fracture toughness K_{IC} .

The fracture surfaces of the four composite materials cyclic loaded at 1 cycle in air was chosen for scanning electron microscope (SEM) examination. The specimens were coated with gold palladium and then observed in a SEM (Hitachi S3000N, Hitachi Scientific Instruments Nissei Sangyo America Ltd, Gaithersburg, MD, USA).

Results

The statistical analyses carried out in this project allow for numerous means of evaluation; i.e., within composite materials, between composite materials, within aging media, between aging media, aged versus unaged for each of the two dependent variables, fracture toughness and cycles completed. However the intent of this paper is to compare the fracture toughness versus the cycles completed for the four composites investigated as unaged (controls) versus 5 month aging between the four aging media (air, distilled water, artificial saliva, and the 50/50 mixture of water and ethanol). The complete detailed statistical analysis of all variables is in Lin [13].

The average number of cycles completed and fracture toughness, K_{IC} are presented in Tables 1–4 for Micronew, Renew, Filtek Supreme Plus, and BelleGlass respectively. Graphical representation of fracture toughness versus cycles completed for the control specimens is given in Figure 1 and the aged specimens in Figure 2.

Overall, the three-way ANOVA (non-aged and aged group, four aging media, four cycling loads) showed a significant difference between non-aged and aged, aging media, and loading cycles. In terms of the number of cycles completed, the non-aged specimens displayed higher mean values compared to the aged specimens in air especially at the 100,000 cycle level. The fracture toughness had a tendency to decrease as the number of cycles increased and was usually lowest in the aged 50/50 mixture.

For the aged specimens in the 50/50 mixture, almost none of the Micronew and Filtek Supreme Plus specimens survived any of four predetermined sets of cycles. On the other hand, none of the BelleGlass HP specimens failed at any of the four loading cycles with Renew somewhat between these two extremes.

The comparison of fracture toughness between the four composites using a three-way ANOVA (four materials, four aging media, four cycles) showed a significant difference between materials, aging media, and loading cycles.

For the unaged specimens in the four media Figure 1, BelleGlass HP displayed the highest fracture toughness at all sets of cycle and Micronew the lowest fracture toughness with Filtek Supreme Plus and Renew having similar fracture toughness between BelleGlass HP and Micronew. One phenomenon worth mentioning is, unlike in air non-aged group where Filtek Supreme Plus and Renew displayed similar fracture toughness at all four loading cycle, the fracture toughness of Filtek Supreme Plus in air aged dropped significantly as the duration of the loading cycles increased.

For the aged specimens, BelleGlass HP still displayed the highest fracture toughness. The fracture toughness of Micronew and Filtek Supreme Plus were zero or close to zero since most of the specimens fractured during cyclic fatigue loading. The fracture toughness values of Renew were close to BelleGlass HP in the 1 and 1,000 loading cycles, but decreased dramatically as the loading cycles increased (10,000 and 100,000).

The SEM observations (Figure 3) of the four composites illustrates the prepolymerized fillers in Renew and Micronew (black areas), the clusters of nanofiller in Filtek Supreme Plus and the large filler particles in BelleGlass HP.

Discussion

BelleGlass HP displayed overall the best resistance to cyclic loading, followed by Renew and Filtek Supreme Plus, and Micronew. BelleGlass HP is a second generation laboratory-processed resin composite (indirect dental composite). This two step polymerization most likely resulted in an increased DC of the monomers. This observed increased in mechanical properties is attributed to a toughening of the filled resin matrix, an improved filler/matrix adhesion, and relief of internal stresses generated during the initial curing by the high temperature treatment, [5].

Filtek Supreme Plus is a nanofilled composite which contains sub-100 nm particles. Non-aged groups of Filtek Supreme Plus showed a similar performance to Renew, a hybrid composite, both in the number of cycles completed in all four loading cycles and also in the fracture toughness under all testing conditions, is in agreement with other studies [3,14]. Aged Filtek Supreme Plus however, showed increased failure during cyclic fatigue loading, and also

showed significantly decreased fracture toughness when compared to Renew. The nanofilled composite has ultra-small filler particles and a subsequent large surface area [15]. The increased susceptibility of Filtek Supreme Plus to aging might be due to increased inter-surface area between ultra-small filler particles and resin matrix which is one of the weakest links in a dental resin composite [16].

Micronew, a microfilled composite is a mixture of 60 ~ 70 wt% of inorganic filler particles and resin matrix, pre-polymerized by the manufacturer, grounded into a powder with particle sizes similar to that of a conventional composite and added to additional resin matrix that contains a small amount of colloidal silica [17].

Microfilled composite has a relatively low filler content (35 ~ 60 wt%), which could contribute to the decrease in the load transfer toughening mechanism and crack pinning toughening [18]. Another detrimental shortcoming of a microfilled composite is poor retention between pre-polymerized organic particles and the resin matrix [14].

In the control groups (Figure 1), none of BelleGlass HP, Filtek Supreme Plus, and Renew specimens fractured during cyclic loading in all four media. For Micronew, air was the media which had the most detrimental effect on the number of cycles completed in all four media investigated; the rest of the media had similar impact on the number of cycles completed except in water at 100,000 cycle level, where the fracture rate was slightly increased than in artificial saliva and in the 50/50 mixture of ethanol and water. In terms of fracture toughness K_{IC} , all four media had a similar result except for Micronew. Micronew showed increased fracture toughness in a sequence of air, water, 50/50 mixture of ethanol and water, and artificial saliva. Micronew has the highest amount of resin matrix of the four composites investigated. Plasticization of the resin matrix by water absorption from the surrounding liquid environment may explain why Micronew had higher fracture rate and lower fracture toughness in air [19]. Plasticization of the resin matrix can blunt the tip of fatigue cracks with less stress concentration, release the internal tensile stress accumulated during polymerization shrinkage, generate residual compressive stress at the tip of a crack and thus make the material less brittle and more fracture resistant. But it has to be emphasized that the toughening of resin composite by plasticization only happens when the material is tested immediately after fabrication, deterioration of composites occurs after long term immersion of composite material in water due to hydrolysis of the resin matrix.

For the aged groups (Figure 2), none of the BelleGlass HP specimens fractured during cyclic loading in all four media; for the remaining three materials, the 50/50 mixture was the most detrimental on the number of cycles completed in all four media investigated, followed by air; water and artificial saliva, which had a similar effect. In terms of fracture toughness, K_{IC} , specimens aged in the 50/50 mixture of ethanol and water displayed the lowest values. The decrease in the fracture toughness following aging in the 50/50 mixture is attributed to the breakdown of the resin and/or a deterioration of the silane bond between the filler particles and the resin [4]. An interesting finding was the fracture toughness of BelleGlass HP aged in air showed the highest value at all four predetermined cycle levels compare to the remaining three media, whereas the fracture toughness of Micronew and Filtek Supreme Plus in air showed a lower value compare to those aged in water at 1, 1,000 cycle levels and at 100,000 cycle level respectively.

Part of the reason for the low result of Micronew and Filtek Supreme Plus is due to the increased fracture rate in air during cyclic loading compared to in water since fracture toughness for those fractured specimens are calculated as zero.

The staircase approach has been utilized in most of the studies investigating the effect of cyclic fatigue on the mechanical properties of dental composites [11,20]. The staircase approach is

an “up-and-down” method. Tests are conducted sequentially with the load in each succeeding test being increased or decreased by a fixed increment, according to whether the previous test resulted in failure or not. Fracture toughness for the material is then calculated according to specific formula [21]. The approach used in this study is an “all-or-nothing” method. Following predetermined number of cyclic loading, the specimens that had completed their respective cycles were tested in three-point loading in their respective media, and the fracture toughness was calculated from the maximum load at which the specimen fractured. For every specimen that fractured during cyclic loading, and thus could not be tested in three-point loading, the K_{IC} value was set to zero. Both methods are intended to investigate the effect of cyclic fatigue on mechanical properties of materials, but the values the investigators get might be different even though the investigators are measuring the same indices.

The limitations in this study were the different notch sizes utilized in this study. Although the notch size does not have effect on the value of fracture toughness theoretically, it would be ideal if there were same notch size for all four materials for better comparison. Longer aging times might show a greater affect for aging on the composites and indicate when BelleGlass might become susceptible to degradation and only one cyclic loading range 5–10 N was used.

Conclusion

Numerous new resin based restorative dental composite materials have been introduced to the market, all claiming superior mechanical properties, excellent esthetics and biocompatibility. The objective of this study was to examine the fracture toughness (K_{IC}) of three direct dental composites, including one micro-filled, one hybrid, and one nano-filled composite and one indirect dental composite, after aging and cyclic loading fatigue in four different environments, namely, air, water, a 50/50 by volume mixture of ethanol and water, and artificial saliva. BelleGlass HP displayed overall the best resistance to cyclic loading, followed by Renew, Filtek Supreme Plus, and Micronew.

Acknowledgments

This investigation was based on a thesis submitted to the graduate faculty, University of Illinois at Chicago, in partial fulfillment of the requirements for the M.S. degree and supported in part by Research Grant DE 07979 from the National Institute of Dental Research, Bethesda, MD 20892. The composites were supplied by 3M-ESPE, Kerr Inc., and Bisco Dental Products.

References

1. Köhler B, Rasmusson CG, Odman P. A five-year clinical evaluation of Class II composite resin restorations. *J Dent* 2000;8:111–116.
2. Burke FJ, Wilson NH, Cheung SW, Mjör IA. Influence of patient factors on age of restorations at failure and reasons for their placement and replacement. *J Dent* 2001;29:317–324. [PubMed: 11472803]
3. Lohbauer U, Frankenberger R, Krämer N, Petschelt A. Strength and fatigue performance versus filler fraction of different types of direct dental restoratives. *J Biomed Mater Res B Appl Biomater* 2006;76:114–120. [PubMed: 16130144]
4. Drummond JL, Lin L, Miescke KJ. Evaluation of fracture toughness of a fiber containing dental composite after flexural fatigue. *Dent Mater* 2004;20:591–599. [PubMed: 15134948]
5. Ferracane JL, Condon JR. Post-cure heat treatments for composites: properties and fractography. *Dent Mater* 1992;8:290–295. [PubMed: 1303369]
6. Kakaboura A, Rahiotis C, Zinelis S, Al-Dhamadi YA, Silikas N, Watts DC. In vitro characterization of two laboratory-processed resin composites. *Dent Mater* 2003;19:393–398. [PubMed: 12742434]
7. Mandikos MN, McGivney GP, Davis E, Bush PJ, Carter JM. A comparison of the wear resistance and hardness of indirect composite resins. *J Prosthet Dent* 2001;85:386–395. [PubMed: 11319537]

8. Asmussen E, Peutzfeldt A. Mechanical properties of heat treated restorative resins for use in the inlay/onlay technique. *Scand J Dent Res* 1990;98:564–567. [PubMed: 2091253]
9. Garoushi S, Lassila LV, Tezvergil A, Vallittu PK. Static and fatigue compression test for particulate filler composite resin with fiber-reinforced composite substructure. *Dent Mater* 2007;23:17–23. [PubMed: 16414110]
10. Braem M, Lambrechts P, Vanherle G. Clinical relevance of laboratory fatigue studies. *J Dent* 1994;22:97–102. [PubMed: 8195483]
11. Abe Y, Braem MJ, Lambrechts P, Inoue S, Takeuchi M, Van Meerbeek B. Fatigue behavior of packable composites. *Biomaterials* 2005;26:3405–3409. [PubMed: 15621229]
12. ASTM PS070–97. Standard test methods for the determination of fracture toughness of advanced ceramics at ambient temperature; 1997.
13. Lin, L. The effects of cyclic fatigue on the fracture toughness of dental composites. Master Thesis Oral Sciences, University of Illinois; Chicago: 2009.
14. Mitra SB, Wu D, Holmes BN. An application of nanotechnology in advanced dental materials. *JADA* 2003;134:1382–1390. [PubMed: 14620019]
15. Papadogiannis DY, Lakes RS, Papadogiannis Y, Palaghias G, Helvatjoglu-Antoniades M. The effect of temperature on the viscoelastic properties of nano-hybrid composites. *Dent Mater* 2008;24:257–266. [PubMed: 17640723]
16. Drummond JL, Lin L, Al-Turki LI, Hurley RJ. Fatigue behavior of dental composite materials. *J Dent* 2009;37(5):321–330. [PubMed: 19181429]
17. Moore, BK.; Oshida, Y. Materials science and technology in dentistry. In: Wise, DL.; Trantolo, DJ.; Altobelli, DE.; Yaszemski, MJ.; Gresser, JD.; Schwartz, ER., editors. *Encyclopedic handbook of biomaterials and bioengineering, Part B: Applications*. Vol. 2. New York: Dekker; 1995. p. 1325-1430.
18. Al-Turki, LI. PhD thesis. University of Illinois at Chicago; Chicago: 2007. Contact cyclic loading of restorative composites.
19. Takeshige F, Kawakami Y, Hayashi M, Ebisu S. Fatigue behavior of resin composites in aqueous environments. *Dent Mater* 2007;23:893–899. [PubMed: 17007919]
20. Lohbauer U, von der Horst T, Frankenberger R, Krämer N, Petschelt A. Flexural fatigue behavior of resin composite dental restoratives. *Dent Mater* 2003;19:435–440. [PubMed: 12742440]
21. Draughn RA. Compressive fatigue limits of composite restorative materials. *J Dent Res* 1979;58:1093–1096. [PubMed: 284043]

a

b

c

d

Figure 1.

The comparison of fracture toughness versus cycles completed for unaged composite specimens in a) air, b) water, c) artificial saliva, and d) a 50/50 mixture of ethanol and water.

a

b

c

d

Figure 2.

The comparison of fracture toughness versus cycles completed for 5 month aged composite specimens in a) air, b) water, c) artificial saliva, and d) a 50/50 mixture of ethanol and water.

Figure 3.
Fracture surface of control specimens a) Micronew, b) Renew, c) Filtek Supreme Plus, and d) BelleGlass HP.

Table 1

The Fracture Toughness and Average Number of Cycles for Microneu

Aging Groups	Aging medium	Cycle groups	Mean KIC	SD KIC	Mean cycles	SD cycles
Non-aged	Air	1	0.82	0.35	0.9	0.4
Non-aged	Air	1000	0.62	0.60	622.5	426.7
Non-aged	Air	10000	0.44	0.56	5448.0	4383.2
Non-aged	Air	100000	0.17	0.44	26803.3	38177.1
Non-aged	Water	1	0.85	0.40	0.9	0.3
Non-aged	Water	0	0.94	0.12	1000.0	0.0
Non-aged	Water	10000	0.77	0.23	9338.1	2563.7
Non-aged	Water	100000	0.55	0.55	64073.4	42470.0
Non-aged	Saliva	0	1.29	0.18	1.0	0.0
Non-aged	Saliva	1000	1.16	0.36	948.8	198.3
Non-aged	Saliva	10000	1.05	0.48	8840.9	3079.8
Non-aged	Saliva	100000	0.97	0.42	87906.5	31955.2
Non-aged	50/50	0	1.62	0.27	1.0	0.0
Non-aged	50/50	0	1.50	0.25	1000.0	0.0
Non-aged	50/50	10000	1.34	0.41	9335.0	2575.5
Non-aged	50/50	100000	1.09	0.41	93700.5	24398.0
Aged	Air	1	0.69	0.45	0.7	0.5
Aged	Air	1000	0.21	0.45	282.7	392.1
Aged	Air	10000	0.00	0.00	129.3	200.1
Aged	Air	100000	0.00	0.00	1682.0	4977.8
Aged	Water	0	0.94	0.12	1.0	0.0
Aged	Water	1000	0.71	0.41	894.2	235.3
Aged	Water	10000	0.17	0.37	4183.1	3814.3
Aged	Water	100000	0.04	0.17	16394.1	27923.4
Aged	Saliva	1	0.80	0.27	0.3	0.3
Aged	Saliva	1000	0.34	0.38	571.5	447.9
Aged	Saliva	10000	0.13	0.35	2610.0	3817.3
Aged	Saliva	100000	0.00	0.00	8021.5	17480.9
Aged	50/50	1	0.00	0.00	0.0	0.0
Aged	50/50	1000	0.00	0.00	15.1	6.7
Aged	50/50	10000	0.00	0.00	14.3	8.1
Aged	50/50	100000	0.00	0.00	147.6	446.4

Table 2

The Fracture Toughness and Average Number of Cycles for Renew

Aging Groups	Aging medium	Cycle groups	Mean KIC	SD KIC	Mean cycles	SD cycles
Non-aged	Air	1	1.41	0.11	1	0
Non-aged	Air	1000	1.35	0.05	1000	0
Non-aged	Air	10000	1.42	0.05	10000	0
Non-aged	Air	100000	1.36	0.10	100000	0
Non-aged	Water	1	1.51	0.07	1	0
Non-aged	Water	0	1.53	0.06	1000	0
Non-aged	Water	10000	1.56	0.07	10000	0
Non-aged	Water	100000	1.56	0.10	100000	0
Non-aged	Saliva	0	1.63	0.188	1	0
Non-aged	Saliva	1000	1.66	0.09	1000	0
Non-aged	Saliva	10000	1.70	0.10	10000	0
Non-aged	Saliva	100000	1.64	0.12	100000	0
Non-aged	50/50	0	1.70	0.13	1	0
Non-aged	50/50	0	1.66	0.16	1000	0
Non-aged	50/50	10000	1.656	0.16	10000	0
Non-aged	50/50	100000	1.706	0.09	100000	0
Aged	Air	1	1.23	0.05	1	0
Aged	Air	1000	1.233	0.04	1000	0
Aged	Air	10000	1.233	0.06	10000	0
Aged	Air	100000	1.29	0.08	100000	0
Aged	Water	0	1.41	0.08	1	0
Aged	Water	1000	1.41	0.05	1000	0
Aged	Water	10000	1.37	0.11	10000	0
Aged	Water	100000	1.24	0.35	94876.7	19842.6
Aged	Saliva	1	1.34	0.07	1	0
Aged	Saliva	1000	1.36	0.08	1000	0
Aged	Saliva	10000	1.35	0.06	10000	0
Aged	Saliva	100000	1.33	0.15	100000	0
Aged	50/50	1	1.01	0.07	1	0
Aged	50/50	1000	1.02	0.07	1000	0
Aged	50/50	10000	0.82	0.27	9943.3	219.7
Aged	50/50	100000	0	0	39935.1	28743.12

Table 3

The Fracture Toughness and Average Number of Cycles for Filtek Supreme Plus

Aging Groups	Aging medium	Cycle groups	Mean KIC	SD KIC	Mean cycles	SD cycles
Non-aged	Air	1	1.40	0.05	1	0
Non-aged	Air	1000	1.41	0.06	1000	0
Non-aged	Air	10000	1.40	0.06	10000	0
Non-aged	Air	100000	1.44	0.06	100000	0
Non-aged	Water	1	1.43	0.08	1	0
Non-aged	Water	0	1.44	0.07	1000	0
Non-aged	Water	10000	1.48	0.09	10000	0
Non-aged	Water	100000	1.42	0.09	100000	0
Non-aged	Saliva	0	1.52	0.06	1	0
Non-aged	Saliva	1000	1.50	0.08	1000	0
Non-aged	Saliva	10000	1.50	0.07	10000	0
Non-aged	Saliva	100000	1.53	0.11	100000	0
Non-aged	50/50	0	1.57	0.06	1	0
Non-aged	50/50	0	1.57	0.07	1000	0
Non-aged	50/50	10000	1.54	0.07	10000	0
Non-aged	50/50	100000	1.53	0.27	100000	0
Aged	Air	1	1.17	0.04	1	0
Aged	Air	1000	1.17	0.03	1000	0
Aged	Air	10000	1.02	0.36	9445.5	1753.5
Aged	Air	100000	0.33	0.53	55751.0	36241.0
Aged	Water	0	1.10	0.07	1	0
Aged	Water	1000	1.07	0.08	1000	0
Aged	Water	10000	1.11	0.10	10000	0
Aged	Water	100000	0.85	0.45	96225.9	11934.8
Aged	Saliva	1	0.78	0.14	1	0
Aged	Saliva	1000	0.82	0.13	1000	0
Aged	Saliva	10000	0.81	0.10	10000	0
Aged	Saliva	100000	0.634	0.46	84613.5	25171.7
Aged	50/50	1	0.40	0.08	1	0
Aged	50/50	1000	0	0	85.3	83.5
Aged	50/50	10000	0	0	50.3	52.0
Aged	50/50	100000	0	0	115.4	111.8

Table 4

The Fracture Toughness and Average Number of Cycles for BelleGlass HP

Aging groups	Aging medium	Cycle groups	Mean KIC	SD KIC	Mean cycles	SD cycles
Non-aged	Air	1	2.06	0.08	1	0
Non-aged	Air	1000	2.04	0.09	1000	0
Non-aged	Air	10000	2.06	0.07	10000	0
Non-aged	Air	100000	2.01	0.05	100000	0
Non-aged	Water	1	2.06	0.10	1	0
Non-aged	Water	1000	2.08	0.09	1000	0
Non-aged	Water	10000	2.07	0.09	10000	0
Non-aged	Water	100000	2.07	0.04	100000	0
Non-aged	Saliva	1	2.05	0.09	1	0
Non-aged	Saliva	1000	2.08	0.09	1000	0
Non-aged	Saliva	10000	2.08	0.07	10000	0
Non-aged	Saliva	100000	2.01	0.10	100000	0
Non-aged	50/50	1	2.05	0.07	1	0
Non-aged	50/50	1000	2.11	0.085	1000	0
Non-aged	50/50	10000	2.09	0.13	10000	0
Non-aged	50/50	100000	2.05	0.09	100000	0
Aged	Air	1	1.91	0.08	1	0
Aged	Air	1000	1.96	0.06	1000	0
Aged	Air	10000	1.96	0.06	10000	0
Aged	Air	100000	1.91	0.07	100000	0
Aged	Water	1	1.80	0.05	1	0
Aged	Water	1000	1.78	0.07	1000	0
Aged	Water	10000	1.78	0.07	10000	0
Aged	Water	100000	1.72	0.12	100000	0
Aged	Saliva	1	1.77	0.04	1	0
Aged	Saliva	1000	1.71	0.07	1000	0
Aged	Saliva	10000	1.78	0.06	10000	0
Aged	Saliva	100000	1.76	0.12	100000	0
Aged	50/50	1	1.37	0.08	1	0
Aged	50/50	1000	1.39	0.09	1000	0
Aged	50/50	10000	1.39	0.05	10000	0
Aged	50/50	100000	1.25	0.19	100000	0