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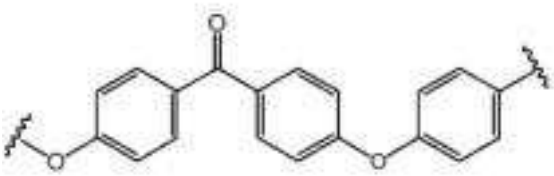
Characterisation of machinable structural polymers in restorative dentistry

1. Introduction

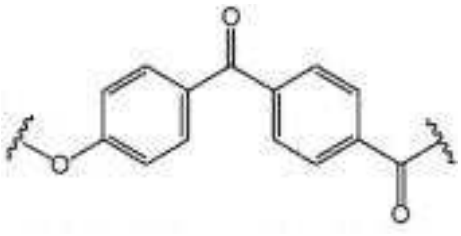
The advent of CAD/CAM in restorative dentistry has increased the range of fabrication technologies beyond polymerisation, casting and porcelain-densification by sintering. Until recently, the focus of CAD/CAM has been on machinable ceramics [1], as polymers were considered to have inferior structural properties making them less desirable restorative materials with unpredictable long-term performance [2].

We are now presented with a new generation of machinable polymers that include highly cross-linked resin based composites (HCL-RBCs) and Resin Infiltrated Ceramics (RICs) such as Lava Ultimate® (3MESPE, Seefeld, Germany) and Vita Enamic® (Ivoclar Vivadent, Schaan, Liechtenstein). These materials represent a new approach increasing the range of treatment options in restorative dentistry [3,4]. An exciting further addition to these groups is the Polyaryletherketones (PAEKs).

PAEKs are a relatively new family of semi-crystalline thermoplastic polymers with high temperature stability and high mechanical strength [5]. They consist of an aromatic backbone molecular chain, interconnected by ketone and ether functional groups [5]. Two commercially available PAEKs used for dental applications (Figure 1) are polyetheretherketone; PEEK (Bredent GmbH & Co. KG, Senden, Germany; Evonik Industries, Essen, Germany; Juvora Ltd. Thornton Cleveleys, Lancashire, UK) and polyetherketoneketone; PEKK (Pekkton®, Cendres-Meteaux, Biel/Bienne, Switzerland).



PolyEtherEtherKetone (PEEK)



PolyEtherKetoneKetone (PEKK)

Figure 1. Chemical structure of PEEK & PEKK

The biocompatibility of the PAEK family was confirmed three decades ago [6] and further studies have supported their long-term biocompatibility [7-9]. Applications of PAEKs in dentistry that are being explored include implant superstructure for fixed arch bridgework and resin-based composite veneered substructure for bridges [10-12]. However, PAEK materials may also offer potential benefits in the provision of full-coverage monolithic dental crowns. PEEK has had more coverage in the literature, however there are very few studies that support the application of PEKK in restorative dentistry [13-16] and there are no independent studies investigating the application of PEKK as a monolithic unveneered restoration.

This work aims to characterise and compare the mechanical properties of all three materials (HLC-RBCs, RICs and PEKK) to determine the applicability of PEKK (PEKKTON®, Cendres-Meteaux, Biel/Bienne, Switzerland) as a material for the provision of a monolithic crown in posterior load-bearing teeth. In line with the current guidance from the Academy of Dental Materials for the testing of properties dental materials, this study aims to characterise these materials by measuring the Biaxial flexural strength (BFS), Vickers Hardness (VH) and the Hygroscopic Expansion Change (HEC) (17). The Structural Strength (SS) of teeth restored with a full coverage crown for each of the three materials was also tested. Wear performance of PEKK was not included in this suite of characterisation tests, as this has been characterised previously (16). The dental literature is guarded about the true value of in-vitro wear testing as the data obtained is often derived from systems that lack qualification, validation and reproducibility. Moreover, as simulators and wear methods differ greatly in their mode of operation, it is not possible to compare the results; which in turn limits the estimation of true clinical performance (17).

2. Materials and Methods

2.1 Sample Preparation of polymeric materials for Biaxial Flexural Strength, Vickers Hardness and hygroscopic expansion experiments

The materials tested were Pekkton® (LOT 200368), Vita Enamic® (LOT 40501) and Lava Ultimate® (LOT 720957). For the biaxial flexural strength (BFS) and Vickers Hardness (VH), sixty specimens were prepared from the three test materials (n=20) with ten samples used for each test. For the hygroscopic expansion change test (HEC), twenty-one specimens were prepared for the three test materials (n=7).

The specimens for the BFS and VH tests were discs produced in accordance with ISO 6872:2008. These were produced by core drilling a block of machinable material (disc or ingot) using a 14mm diamond core drill. The resulting cylinders were subsequently sectioned into four discs using a precision saw IsoMet 1000 (Buehler, USA) and finished with 35μm-grit and 18.3μm-grit SiC paper on a grinder/polisher Buehler Metaserv (Buehler UK ltd, UK). The final thickness of each specimen was measured over three equidistant points and averaged. The resulting disc specimens were 14mm diameter with a mean thickness 1.13 mm ±0.02 mm.

The specimens for the HEC tests were discs 12mm diameter x 1mm height. These were produced by core drilling a block of machinable material (disc or ingot) using a 12mm diamond core drill. The resulting cylinders were subsequently sectioned into discs and polished in the same manner as that described above for the BFS and VH tests. The resulting disc specimens were 12mm diameter with a mean thickness 1.08 mm ±0.05 mm.

2.2 Sample Preparation of Ceramics for Biaxial Flexural Strength, & Vickers Hardness

For the biaxial flexural strength (BFS) and Vickers Hardness (VH), twenty specimens were prepared (n=20) with ten samples used for each test. Ceramic discs were made from IPS e.max Press ingots using a ceramic furnace Programat EP 3000 (Ivoclar-Vivadent, Germany) following the firing cycle recommended by the manufacturer. Further grinding and polishing using

the same methodology described above was used to obtain the final specimens.

2.3 Replica teeth preparation for Structural Strength Experiment

Forty identical tooth replicas (N=40) were made from a polyurethane-based die material (AlphaDie® MF, Schütz Dental GmbH, Rosbach, Germany). A lower first permanent molar tooth (Frasaco, GmbH, Tettnang, Germany) was prepared with an occlusal reduction of 2mm and 1mm cervical margin chamfered finish using a 12º taper. This provided a master die that was duplicated 40 times using a silicone mould (Provil Novo Putty, Heraeus Kulzer, Germany) into which the AlphaDie® was poured. The roots of each replica tooth were dipped into liquid wax (Sabilex de Flexafil S.A.), which acted as a separating medium and spacer before being placed into a copper ring filled with AlphaDie®. Once the AlphaDie® base had set, the tooth was removed from the base and the wax removed using a steam gun, the base was then filled with light bodied silicone (President, Coltene/Whaledent, Switzerland) and the die replaced and the excess silicone was removed with a wet piece of gauze. This allowed each replica prepared tooth to be mounted in a bone-like socket made from silicone putty encased in an AlphaDie® MF base contained by a copper ring (Figure 2). AlphaDie® was chosen as it possesses an elastic modulus similar to that of dentine [18] and bone [19]. It has also been extensively used in the literature as a dentine-like material for in-vitro based studies [20, 21].

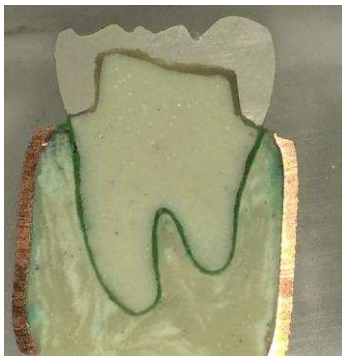


Figure 2. Cross-section of replica prepared tooth encased in AlphaDie®

2.4 Crown fabrication

Each prepared duplicate tooth was digitally scanned (Identica Blue, Medit Corporation, Korea) to obtain a digital model upon which a crown was designed using proprietary software. (DentalCad, Exocad GmbH). From this design ten (n=10) crowns were milled in Lava Ultimate®, Vita Enamic®, Pekkton® and in wax to obtain the pattern for the pressing procedure for IPS e.max Press® using the Roland DWX-50 milling unit (Roland DG Corporation).

2.4. Cementation Technique

The crowns were cemented on to the replica prepared teeth using a self-adhesive cement; Multilink Automix (Ivoclar Vivadent AG, Schaan, Liechtenstein) (LOT U03166) as per the manufacturers instructions [22].

Crown cementation followed the protocol detailed in Table 1.

	Die	Vita Enamic®	Lava Ultimate®	IPS e.max Press®	Pekkton®
Pre-treatment	-	HF 5% (1 min)	Grit-blasted 50µ Al_2O_3	HF 5% (20 sec)	Grit-blasted 50µ Al_2O_3
Cleaning	Alcohol	Water	Alcohol	Water	Water
Dry	Oil-free compressed air – 10 seconds				
Bonding application (20 sec)	□	□	□ (scrubbing)	□	□
Air thinning (5 sec)	□	□	□	□	□
Cement application	-	□	□	□	□
Curing time (per surface)	20 seconds				

Table 1. Crown cementation protocol

A Lloyd LRX universal testing machine (Lloyd Instruments, UK) was used to apply a 40N pressure for 3 minutes for cementing each crown using a silicone mould (Aquasil Putty®, blue colour, Dentsply-Detrey AG, Konstanz, Germany) of the occlusal surface of the crown. This methodology simulates the load and force distribution achieved with finger pressure and ensures standardisation

[23]. (**Figure 3**)

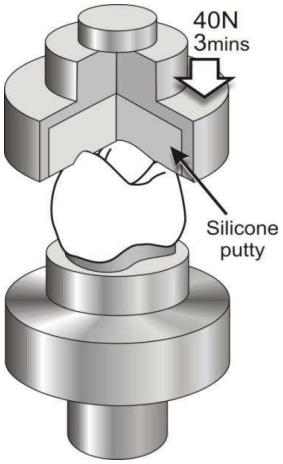


Figure 3. Diagrammatic representation of crown cementation procedure using silicone rubber mould and Lloyd LRX testing machine

Each restored tooth was inserted in its "socket" using light-bodied silicone (President®, Coltene/Whaledent, Switzerland) to mimic the viscoelastic properties and dimensions of the periodontal ligament [24] and then stored for 24 hours at room temperature.

The duplicate restored teeth (Pekkton® crowns and PDL) were used for structural strength experiments.

2.5 Biaxial Flexural Strength (BFS)

Specimen discs of all materials (n=10) were tested with a biaxial flexural strength fixture (piston on three ball) in accordance with ISO 6872:2008 (Figure 4). The thickness was measured at the centre of each disc using a digital micrometer (Mitutoyo Corp, Tokyo, Japan). The specimens were located centrally on the supporting balls between 2 sheets of polyethylene film to evenly load distribution. A load was applied with a crosshead speed of 1mm/min using a Lloyd LRX universal testing machine (Lloyd Instruments, UK). The maximum load causing fracture was registered for each specimen and used to calculate biaxial flexural strength with the following equation (ISO 6872:2008):

$\sigma = -0.2387\ P(X - Y)/b^2$

where;

σ is the maximum centre tensile stress, in megapascals;

P is the total load causing fracture, in Newtons;

$X = (1+v)\ln(B/C)^2 + [(1-v)/2](B/C)^2$

$Y = (1+v)[1+\ln(A/C)^2] + (1-v)(A/C)^2$

b is the specimen thickness at fracture origin in millimetres;

v is Poisson's ratio;

A is the radius of support circle in millimetres;

B is the radius of loaded area, in millimetres;

C is the radius of specimen, in millimetres;

For the present study A: 6mm; B: 0,7mm and C: 7mm. Poisson's ratio for Enamic®: 0.23 [25], Lava Ultimate®: 0.25 [26], IPS e.max Press: 0.23 [27] and Pekkton®: 0.40 [28].

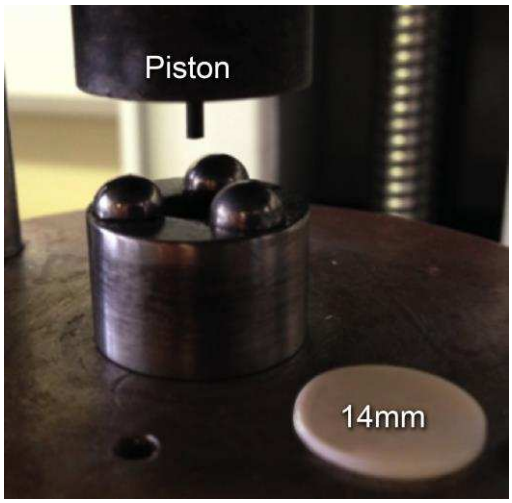


Figure 4. Piston on 3 balls Jig

2.6 Vickers Hardness (VH)

Ten of the prepared discs (n=10) were used for the Vickers Hardness test. Five indentations were made in each sample using a load of 10kg and a dwell time of 20 seconds in a Vickers hardness tester, Foundrax VX series (Foundrax, UK). The value of each indentation was obtained using digital processing software (In2View HT, Mitutoyo Corp, Tokyo, Japan).

2.7 Hygroscopic Change

Twenty-one specimens (n=21) consisting of three groups of seven specimens were tested for each material. Two specimens from each group were used as controls and were retained in a desiccating chamber at 37 ℃ to act as the control. The remaining five specimens of each group were immersed in artificial saliva at 37 ℃, stored individually in sterile sample pots. The artificial saliva had a neutral pH with a composition of sodium carboxymethylcellulose, xylitol, calcium chloride, dibasic potassium phosphate, sodium chloride, potassium chloride and methyl hydroxybenzoate [29-31]. The specimens were gently agitated at periodic intervals and the storage medium replaced after each measurement.

Changes over time due to water sorption are measured by obtaining a volumetric measurement of the dimensional changes and by recording the change in weight. The methodology used in this experiment for measuring these dimensional changes due to water sorption for the three materials has been previously reported [29-31].

The linear diameter change of the discs was measured using a linear micrometer [29-31] and then, by means of a mathematical calculation, the volumetric change of the specimens is determined. The volumetric change at each time point was calculated from the linear change using the formula (Equation 1):

$$Volume\ change\ (\%) = ((1 + (linear\ change(\%)/100)^3 - 1))\ x\ 100$$

Equation 1. Volumetric Change Equation

Changes in weight were measured with a calibrated electronic microbalance (Mettler AE50, Mettler Toledo, Inc., Columbus, OH) to a resolution of 0.1 μg [29-31]. Before scanning and weighing the specimens; each specimen was removed from its storage medium, gently dried with blotting paper and left undisturbed for 4 minutes in order to allow stabilisation [29-31]. All measurements were recorded at the following time points: At the end of a 48 hour conditioning period and then after immersion at intervals of 1, 2 and 5 days and then at weekly intervals for 63 days, in accordance with previously

published protocols [29-31].

2.8 Structural Strength Test

Each restored tooth was firmly secured in the base of a 4.2mm steel ball indenter jig (Figure 5). A static compressive load was applied on the central occlusal area (1mm thickness) until fracture using a LRX Lloyd universal testing machine (Lloyd Instruments, UK) at a crosshead speed of 1mm/min.

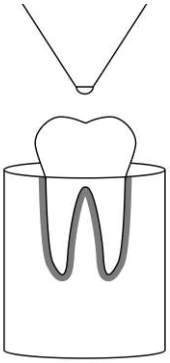


Figure 5. Diagrammatic representation of Structural Strength Test

As a stress breaker, a polyethylene film was interposed between occlusal surface and ball indenter prior to testing. For each specimen, the maximum load causing catastrophic failure was registered in Newtons (N).

Following the structural strength test, representative samples were prepared in cross section for light microscope examination with a SteREO®, Discovery V8, Zeiss at 8:1 magnification to examine the structural changes within the crown tooth complex (adhesive lute interface and dentine structure). Samples were embedded in clear cold cure acrylic and sectioned through the long axis of the tooth using the precision saw IsoMet 1000 (Buehler, USA). The samples were then polished using 35µm-grit and 18.3µm-grit SiC paper on a grinder/polisher (Buehler Metaserv (Buehler Ltd, UK) prior to examination under light microscope.

2.9 Statistical analysis

Mean values and standard deviations for biaxial flexural strength, Vickers

hardness, hygroscopic change and structural strength tests were calculated for all the materials tested. Data was analysed and compared using one-way ANOVA with post hoc Tukey's test at a level of 5% significance to determine difference between groups using statistical software SPSS v.22 (IBM Corp., USA).

RESULTS

Biaxial Flexural Strength

The mean BFS values of the materials tested are presented in Table 2. The difference in BFS between IPS e.max Press® and other materials tested was statistically significant ($p<0.0001$).

MATERIAL	Number of samples	MEAN BFS (Mpa)	Std.Deviation
VITA ENAMIC®	10	137	7
LAVA ULTIMATE®	10	145	18
IPS e.max PRESS®	10	317	37
PEKKTON®	10	227	18

Table 2. Mean Biaxial Flexural Strengths of Materials Tested

Vickers Hardness

The results of the Vickers hardness testing are shown in Table 3.

Material	Number of indentations	Mean (Mpa)	Std. Deviation
VITA ENAMIC®	50	1976	12
LAVA ULTIMATE®	50	924	27
IPS e.max PRESS®	50	5064	131
PEKKTON®	50	445	21

Table 3. Mean VH values of the materials tested (5 indentations per sample)

Statistical analysis (ANOVA) revealed significant differences between each group when comparing hardness ($p<0.0001$). Further inter-group comparison

(Tukey's test) demonstrated significant differences between Vita Enamic®, compared to Lava Ultimate® ($p<0.0001$) and IPS e.max Press® ($p<0.0001$) and between Lava Ultimate® and IPS e.max Press® ($p<0.0001$).

Hygroscopic Change

At 68 days of immersion in a solution of artificial saliva, all three polymeric materials showed linear, weight and volume changes. Pekkton® demonstrated the lowest mean linear change of 5.6µm, Vita Enamic® showed a mean linear change of 15.2µm and Lava Ultimate® had the greatest mean linear change, 42µm. When comparing linear, weight and volume changes across groups using one – way ANOVA there was a statistically significant difference between groups; post hoc tests identified that Lava Ultimate® had the worst outcome ($P<0.0001$ in each category). Post Hoc tests comparing Pekkton® against Vita Enamic® showed no statistically significant differences in each category. The mean linear changes can be seen overall in Table 4.

Material	N	Mean Linear Change (µm)	Std Deviation (µm)	Mean Weight Change (µg)	Std Deviation (µg)	Mean Volume Change (%)	Std Deviation (%)
Vita Enamic®	5	15	6.3	0.46	0.71	0.38	0.16
Lava Ultimate®	5	4	6.5	-41.34	29.82	1.06	0.16
Pekkton®	5	6	5.6	0.36	0.56	0.14	0.14

Table 4. Mean Hygroscopic Change of the materials tested

Pekkton® showed the smallest change in weight with a mean increase in weight of 0.36µg, Vita Enamic® showed a slightly increased weight change with a mean weight gain of 0.46µg and Lava Ultimate® showed a mean weight loss of 41.34µg. Pekkton® showed the greatest dimensional stability with the lowest increase in volume change (0.14% S.D=0.14), followed by Vita Enamic® (0.38% S.D. = 0.16). Lava Ultimate® showed the largest change in volume (1.06% S.D. = 0.17).

Structural Strength Test of full coverage Pekkton® crown

The mean load to fracture and standard deviation values at maximum load

fracture are presented in Table 5

Material	N	Mean Load to Fracture (N)	Std Deviation
Vita Enamic®	10	1127	108
Lava Ultimate®	10	1476	142
IPS e.max Press®	10	1497	165
Pekkton®	10	2037	49

Table 5. Mean Load to Fracture and Standard Deviations of materials tested

Pekkton® showed no signs of failure and at the maximum of 2037N Pekkton® showed higher values than any other material tested ($p<0.001$). Vita Enamic® exhibited lower structural strength than all other materials ($p<0.001$). Light microscope examination with SteREO®, Discovery V8, Zeiss at 8:1 magnification of the prepared post test samples, revealed minimal subsurface damage of the cement layer/fracture of the cemental interface (Figures 6 & 7). There were minimal signs of compression of the Pekkton® crown with reduced thickness when compared to other sites of the crown that were not in contact with the steel indenter.

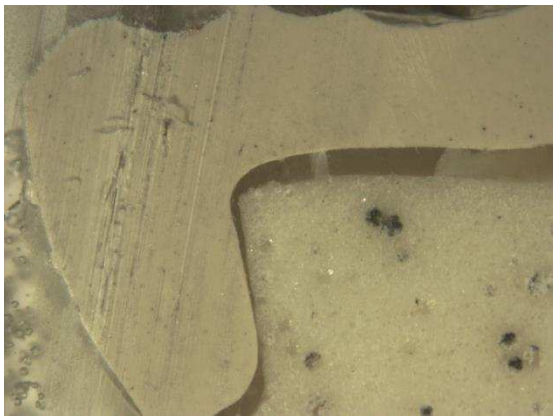


Figure 6 Section of Pekkton® crown under light microscope

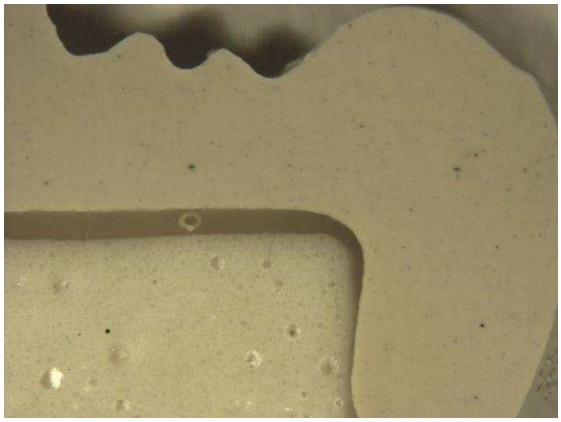


Figure 7 Section of Pekkton® crown examined under light microscope

Discussion

In this study we have characterised properties that are key to the use of PEKK as a full coverage monolithic (single component) crown restoration. Although long-term randomised controlled trial studies provide the ultimate basis by which we can predict the long-term performance of such restorations, these must be preceded by the characterisation of their physical and mechanical properties in a comparative manner [32]. Laboratory mechanical testing is considered a pre-requisite to any clinical investigation which, can provide a moderate positive correlation with clinical outcomes (17)

The experimental tests that were selected to compare and rank PEKK to current alternative structural polymer materials designated for use as permanent full coverage crowns are considered to provide independent baseline comparative data of the physical characteristics of these materials in both standard sample mode and in the constructional form of a full-coverage crown adhesively cemented onto a tooth.

Following the investigation detailed in this study with Lava™ Ultimate® (3M ESPE), the manufacturers have issued a 'Change in Indication' notice for Lava™ Ultimate® (3M ESPE) "because crowns are debonding at a higher-than-anticipated rate and therefore not consistently meeting 3M's high standards for quality and performance" [33]. In the same notice, the 3M company state that the product (Lava™ Ultimate®) "continues to be indicated for inlays, onlays (with an internal retentive design element) and veneer restoratives, per new Instructions For Use (IFU)" [33]. Hence, despite the change in indication for this material, it remains pertinent to characterise this material and compare it to other structural polymer materials indicated for the restoration of structurally compromised teeth.

The methodology used for the BFS was informed by ISO 6872:2008. This ISO test standardises the configuration of the test specimens in terms of thickness, diameter and the roughness. For brittle materials, measurement of biaxial flexural strength rather than uniaxial flexural strength is considered

more reliable as the maximum tensile stresses occur in the central loading areas rather than the edges [34]. Therefore, edge failures are eliminated and there is less variation in the data [35]. The biaxial flexural strength of Pekkton® (227 MPa S.D 18MPa) was significantly higher than the other polymeric materials tested [Vita Enamic®, 137 MPa (S.D. 7MPa); Lava Ultimate®, 145 MPa (S.D. 18MPa) but significantly lower than the value achieved by IPS e.max Press® (317 MPa S.D. 37MPa). Comparison of mean biaxial flexural strength scores using a one-way Anova demonstrated a significantly increased biaxial flexural strength compared to the other materials tested. There was no statistically significant difference in the biaxial flexural strength between the other polymeric materials.

Of the three polymeric materials tested, PEKK had the lowest Vickers Hardness, with a value close to that of human dentine (559–588 MPa) [36]. This data, based on flat specimens, would suggest a higher susceptibility to surface degradation and wear, which in turn may lead to an increase in surface roughness and a higher plaque accumulation [37]. The existing literature suggests that the wear resistance of PEKK materials has an acceptable clinical performance (16). Conversely, a softer material is also attributed with reduced wear of the antagonist tooth [38]. The hardness value of these materials may substantiate the manufacturer's decision to limit the application of the material to its use as a long-term transitional/temporary crown material. It is important to note that the Vickers Hardness of PEKK compares similarly when compared to the hardness values of direct placement resin-based composites used for the restoration of occlusal surfaces of posterior teeth [39,40]. Furthermore, a reduced value for the Vickers Hardness should not be considered in isolation, as this alone does not necessarily equate to a higher wear rate. The wear rate is also dependent on the coefficient of friction of the material. PEKK has a low coefficient of friction [41] as a non-particulate material and therefore further laboratory wear studies and creep testing may provide more conclusive evidence in this respect and help determine the suitability of the material for a more permanent use.

Materials placed in the oral cavity for long periods of time will interact with the

oral fluids. This interaction may take the form of leaching out of components within the material, dissolution of the surface layer or absorption into the material [42]. Absorption within the material may cause dimensional changes and may affect the mechanical properties of the material. This may have clinically relevant implications dependent upon the applied role of the material. Volumetric expansion of resin-based polymer materials has been reported to range between (0.7 - 1%), dependent on the material [43]. These values are within a similar range reported for polymerisation shrinkage on setting [29-31]; substantiating the hypothesis that hygroscopic expansion may compensate for polymerisation shrinkage and thus help to reduce the effect of polymerisation shrinkage stress at the material-tooth adhesive interface. Notwithstanding, it would seem that hygroscopic expansion does not always cause complete closure of contraction gaps around composite filling materials [44]. With respect to the polymeric materials tested, any increase in dimension resulting from hygroscopic expansion would be considered to be deleterious as these are all machined pre-polymerised materials.

All the polymeric materials tested showed an increase in volume when immersed in artificial saliva over a 68-day period. The pattern of change for the RICs was linear up to day forty with relative stabilisation thereafter. PEKK specimens showed minimal change over the entire duration of the study. Given the data accumulated over this period, it was postulated that there would be little or no change thereafter and an arbitrary figure of 68 days was used as the endpoint based on these results and previous studies [29-31]. Lava Ultimate® showed the greatest mean volume change (1.06%), which was more than double that of Vita Enamic® (0.38%) and more than six-fold that recorded for Pekkton® (0.14%). Whilst all three materials have scored low values, with no consensus of an ideal value, and unlikely to be of any clinical consequence, it is logical to suggest that a near zero value is desirable [29].

PEKK (Pekkton®) crowns offer excellent structural strength in the form of a monolithic crown although it is recognised that there is no single in-vitro test able to fulfil all the oral conditions [45]. The structural (integrity) strength test

is considered by the authors as more valuable in terms of clinical importance when selecting these materials than other strength tests; this is especially so having standardised the specimen preparation (teeth and PDL), the geometry of the crown and the test conditions in this study. A study of this type, that seeks to characterise the mechanical performance of a restorative material, requires that all other variables be controlled as far as possible. There is a significant variation amongst natural teeth in terms of its morphology, structural and ratio of inorganic: organic composition. The use of an appropriate dentine replica material, with closely matched physical and mechanical properties achieves this. Notwithstanding, it is recognised that dentine has an isotropic structure by virtue of its tubular form, while AlphaDie® is isotropic by virtue that it is a composite with evenly dispersed particles, which may lead to different mechanical behaviour under loading conditions. The polyurethane-based resin material has been used extensively in the literature for this type of study as it has it has an elastic modulus closely matched to that of dentine [18], similar to bone [19], and has the ability to bond to the composite luting cement. It is widely used in the literature as dentine-like material [20,21]. However, it should be noted that AlphaDie® has a different structural design than dentine.

PEKK crowns cemented on teeth analogues, as per the test performed in this study, appeared to perform significantly better than the RICs and the ceramic crowns IPS e.max® Press crowns. No visible structural failures were observed with the PEKK crowns, that withstood the loads in excess of 2000N in comparison to the catastrophic fracture of the RIC crowns (1127 N for Vita Enamic® and 1476 N for Lava Ultimate®) and the IPS e.max® ceramic crowns (1497 N).

The PEKK crowns did demonstrate evidence of minimal plastic deformation at the points of load application. However, the forces generated in this test far exceeded normal masticatory forces. It is generally accepted that restorations are submitted to masticatory forces ranging from 100N to 500N depending on the region within the oral cavity [46] as well as gender, age; body mass index and type of occlusion [47]. Furthermore, the greatest occlusal forces are

generated in the molar region (first molar) [46] which may be even as high as 900-1000N in cases of severe parafunctional bruxing habits [46], which are much lower parameters than the crowns were subjected to.

The authors recognise that the structural Integrity/compressive crunch test does not replicate a natural occlusal loading and as such is not an effective indicator of clinical performance [48]. Notwithstanding and accepting this limitation, it does provide an effective indicative baseline test for determining the structural performance of new restorative systems prior to undertaking any further clinical investigations. It is of value when there is no previous history of structural integrity and allows us to ascertain that the crown will not fail the moment that the patient occludes on it. Without that assurance, there is no validity in proceeding to studies on durability whether in vitro or in vivo. It is recognised that the results from this test have limited value and should be viewed collectively with the properties of the materials.

The information gained from the tests we undertook supports the potential use of PEKK as a monolithic full coverage permanent restoration.

Conclusions

This study shows that PEKK in the form of a full coverage unveneered monolithic crown provides the basis for a restoration with adequate mechanical and physical properties for use as a permanent monolithic crown when compared with other materials by the same parameters. A pilot prospective cohort study to test monolithic un-veneered PEKK crowns would provide more information of their clinical performance and may substantiate a larger scale fully randomised controlled trial in the future if the pilot trial proved successful.

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