Characterization of the mechanical properties of CAD/CAM polymers for interim fixed restorations

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This study investigated some mechanical properties of five CAD/CAM materials used for the fabrication of provisional restorations and tooth segments for digitally fabricated dentures. The CAD/CAM blocks were sectioned into bars for flexural strength and elastic modulus testing (n=80), and for surface microhardness (n=80). Half of the specimens were water-stored for 30 days while the other half was dry-stored. Additional specimens were prepared for bond strength (n=40). A 2-way analysis of variance (ANOVA) was conducted to detect the effect of material and water storage (α=0.05). The type of material did not have a significant effect on bond strength (p>0.05). The tested materials showed variation in their flexural properties and surface microhardness whereas their bonding properties with resin luting cement were similar.

Keywords: CAD/CAM, PMMA, Digitally fabricated dentures, Flexural strength, Surface hardness

INTRODUCTION

The composition and quality of the materials used for the construction of temporary crowns and bridges are essential for the treatment outcomes of fixed prosthetic restorations⁶. They are placed intraorally during the period between tooth preparation and cementation of the final restoration. In the case of implant-supported restorations, interim prostheses on immediately or conventionally loaded implants are crucial to restore function and esthetics during the osseointegration period, as well as to manage the healing of soft tissue around the implants⁶-⁸. Accordingly, these types of restorations have to fulfill certain biological, esthetical, and mechanical requirements⁸.

The favorable outcomes of interim restorations depend on various factors, including their ability to withstand masticatory forces⁹. Additionally, they protect the prepared tooth structure, the pulp, and the periodontal ligament in the case of natural teeth⁶-⁸, as well as to shape and preserve the coronal mucosa surrounding dental implants⁸ in the case of implant-supported restorations. They are placed intraorally immediately after their fabrication, being subjected to functional loading during mastication¹⁰. Interim prostheses are commonly used for extended time when they are associated with implant rehabilitation or comprehensive occlusal reconstruction procedures¹¹,¹².

Commonly, over impression technique is used to fabricate interim restorations where templates of the desired morphology are filled with resin material and placed on the prepared tooth¹⁰. These procedures are considered time-consuming and could also lead to voids incorporation within the restoration affecting its mechanical properties and marginal integrity¹⁴. Laboratory processed restorations which are based on polymethyl methacrylate (PMMA) are frequently used as interim prostheses, however, high incidence of fractures have been reported although the prostheses can be specifically reinforced¹⁵-¹⁷. Furthermore, conventionally manufactured PMMA based temporary restorations have lower color stability and increased polymerization shrinkage which affects precision of fit. Some reports show their association with lower values of flexural strength immediately after their manufacturing process¹⁵,¹⁶.

Computer assisted design/computer-assisted manufacture (CAD/CAM) technologies have been introduced for the fabrication of interim restorations. Polymers which have various cross-linking densities are used for fabricating CAD/CAM provisional restorations¹⁸,¹⁹. These cross-linked materials provide different mechanical properties depending on their chemical composition²⁰,²¹. The manufactures of these kinds of products as well as some researchers have reported their higher mechanical properties, better color stability, and more accurate marginal fit when compared with the conventionally polymerized resin²⁰,²¹-²³. Additionally, they are considered to be time-saving²⁰, and of easy machining without the need for reinforcement such as fibers or metal wires¹⁷,²⁵,²⁶.

The mechanical properties of interim restorations are of particular significance as they might affect the integrity of temporary reconstructions when they are exposed to functional loads²⁷. Therefore, the aim of this study was to investigate some mechanical properties of five CAD/CAM materials used for the fabrication of provisional restorations and tooth segments for...
digitally fabricated dentures. The mechanical properties investigated were flexural strength, flexural modulus, surface microhardness and bond strength to an adhesive resin cement under two different storage conditions. Our research hypothesis was that the differences in the materials and the storage conditions would significantly affect the evaluated properties.

MATERIALS AND METHODS

In the present in vitro study, a variety of CAD/CAM materials were evaluated: Degos Dental L-Temp Multicolor (Degos Dental, Regenstauf, Germany), SR Vivodent CAD (Ivoclar Vivadent, Schaan, Liechtenstein), Zirkonzahn Temp basic (Zirkonzahn, South Tyrol, Italy), Zirkonzahn Multistratum flexible (Zirkonzahn), and Harvest ZCAD™ Temp Esthetic (Harvest Dental Products, Brea, CA, USA). The tested materials are used for fabricating provisional restorations except SR Vivodent CAD, which is a tooth material used for digitally fabricated dentures. The tested materials are listed in Table 1.

**Flexural strength and flexural modulus testing**

For each material, blocks were sectioned using a water-cooled diamond saw (Struers Secotom-50, Ballerup, Denmark) into equal bar-shaped (2×2×25 mm) specimens. For each material type half of the specimens were tested after 1 month of dry storage (n=8) while the other half was stored for 30 days in distilled water at 37°C before testing. A static 3-point bending test (Model LRX, Lloyds Instruments, Hampshire, UK) was performed in air to determine the flexural strength and flexural modulus. The testing machine was programmed to a constant displacement rate of 1 mm/min, a pre-load of 1.0 N, a pre-load speed of 10 mm/min and the distance between the supports of the test specimens was 20 mm. The test was considered finished when the current load was reduced to 50% of the maximum load or was less than 1.0 N.

**Surface microhardness testing**

Eighty specimens of (4×10×10 mm) were obtained (n=16/material). They were wet ground flat with 1200 grit (FEPA) silicon carbide grinding paper. The specimens were then cleansed in deionized water in an ultrasonic cleaning device (Quantrex 90, L&R Ultrasonics, Kearny, NJ, USA) for 10 min. Half of the specimens were stored dry while the rest were stored in distilled water at 37°C for 30 days. Surface microhardness testing was performed on selected portions of the specimens with a Vickers hardness testing machine (Duramin-5, Struers). The force used was 245.2 mN for 15 s. One indentation was made on each specimen to obtain the surface microhardness value and the deformation of the indentation was measured after 3 s from the point of releasing the load.

**Bond strength**

An autopolymerizing acrylic resin (Palapress, Kultzar, Hanau, Germany) was used as a base material into which the CAD/CAM materials were embedded (20×10×2 mm). A total of forty specimens were prepared (n=8/material). The specimens were wet ground flat with 1200 grit (FEPA) silicon carbide grinding paper and afterwards cleansed in deionized water in an ultrasonic cleaning device (Quantrex 90, L&R Ultrasonics) for 10 min and allowed to dry under ambient laboratory conditions (23±1°C).

The bonding surfaces of the specimens were next treated with a universal adhesive (Scotchbond, 3M ESPE, St. Paul, MN, USA) using a fine microbrush following the manufacturer’s recommendations. Thereafter, self-adhesive resin cement (Relyx Unicem, 3M ESPE) was applied in 1 mm increments to the substrate surface using a translucent polyethylene mold, with a diameter of 3.6 mm and height of 4 mm. Each specimen was then photopolymerized with a hand-held light-polymerizing unit (Elipar S10, 3M ESPE) for 40 s. Next, the specimens were stored in dry conditions for 24 h at room temperature (23±1°C). Bond strength testing was performed with a universal testing machine (Model LR 30K plus, Lloyds Instruments). Data were recorded with data analysis software (Nexygen, Lloyd instruments). The specimens were loaded at the interface of the substrate and the resin cement at a 1.0 mm/min crosshead speed until fracture occurred. Bond strengths were calculated in MPa. The fracture modes of the samples were analyzed visually and classified as adhesive or cohesive failures.

A specimen of each material was placed in Tetrahydrofuran (THF; Sigma-Aldrich, St. Louis, MN, USA) for 10 min. This was made in order to identify differences in the materials’ cross-linking densities. An

**Table 1  Materials used**

| Material                  | Manufacturer          | Indication                                           |
|---------------------------|-----------------------|------------------------------------------------------|
| L-Temp Multicolor         | Degos Dental          | Long-term temporary restorations                     |
| SR Vivodent CAD           | Ivoclar Vivadent      | Tooth segments in removable denture prosthetics      |
| Temp basic                | Zirkonzahn            | Short-term temporary restorations                    |
| Multistratum flexible     | Zirkonzahn            | Long-term provisional restorations                   |
| ZCAD™ Temp Esthetic       | Harvestdental         | Long-term provisional restorations                   |
evaluation of the gold sputtered surfaces was performed with a scanning electron microscope (SEM; JSM 5500, Jeol, Tokyo, Japan) to visually analyze the polymer structure of the different CAD/CAM materials.

All data for flexural strength, flexural modulus, surface microhardness, and bond strength were collected and statistically analyzed. A 2-way analysis of variance (ANOVA) was conducted to detect the effect of material and water storage as the independent variables on the evaluated properties ($\alpha=0.05$). Statistical software (IBM SPSS Statistics v21, IBM, Redmond, WA, USA) was used for conducting all analyses.

RESULTS

The statistical analysis by 2-way ANOVA showed that material type and water storage significantly affected the flexural strength, flexural modulus and surface microhardness ($p<0.001$). Additionally, the interaction between material and water storage was significant ($p<0.001$). Material type did not seem to have a significant effect on bond strength ($p>0.05$) (Fig. 1). The mean values for flexural strength, flexural modulus, and surface microhardness of the tested groups are presented in Table 2.

For dry specimens, the mean flexural strength and flexural modulus values of Zirkonzahn Temp basic specimens were significantly lower than the other 4 materials ($p<0.001$). Figure 2 shows a load-deflection graph as a graphic representation of the behavior of the tested materials. A non-significant difference was found for flexural strength among Zirkonzahn Multistratum flexible, SR Vivodent CAD, L-Temp multicolor, and ZCAD™ Temp ($p=0.207$).

For flexural modulus, SR Vivodent CAD specimens were significantly higher than Zirkonzahn Temp basic and Zirkonzahn Multistratum flexible ($p<0.001$) for water and dry-stored specimens, and not significantly different from ZCAD™ Temp Esthetic and Degos Dental L-Temp Multicolor ($p>0.05$). For surface microhardness under dry and wet conditions, Zirkonzahn Temp basic and Zirkonzahn Multistratum flexible specimens recorded the lowest values, which were significantly different from the other 3 materials ($p<0.001$). SR Vivodent microhardness values were not significantly different from L-Temp Multicolour and ZCAD™ Temp Esthetic with the two storage conditions ($p>0.05$).

Visual examination revealed only adhesive failure types for all tested materials after bond strength testing. Additionally, only specimens fabricated from Zirkonzahn Multistratum flexible bended without fracturing when subjected to flexural strength testing.

Fig. 1 Bond strength of tested materials.

![Fig. 1](image1)

![Fig. 2](image2)

**Table 2** Mean flexural strength (FS), flexural modulus (FM), and surface microhardness values of the materials investigated

| Material                     | FS (MPa)       | FM (GPa)       | Surface hardness (VHN) |
|------------------------------|----------------|----------------|------------------------|
|                              | Dry | Water | Dry | Water | Dry | Water |
| Degos Dental L-Temp MC       | 102 (8)$^a$ | 108 (12)$^a$ | 3.0 (0.3)$^a$ | 3.1 (0.8)$^{ac}$ | 22 (0.7)$^a$ | 21 (0.3)$^a$ |
| SR Vivodent CAD              | 105 (11)$^a$ | 117 (11)$^{ac}$ | 3.0 (0.2)$^a$ | 3.7 (0.4)$^{ad}$ | 22 (0.8)$^{ac}$ | 20 (0.5)$^a$ |
| Zirkonzahn Temp Basic        | 74 (12)$^b$  | 64 (12)$^b$  | 1.6 (0.2)$^b$  | 1.1 (0.1)$^b$  | 16 (0.5)$^b$  | 12 (0.6)$^b$  |
| Zirkonzahn Multistratum Flexible | 109 (12)$^a$ | 124 (8)$^c$ | 2.2 (0.3)$^c$ | 2.7 (0.4)$^c$ | 17 (0.9)$^b$ | 15 (0.6)$^c$ |
| Harvest Temp Esthetic ZCAD   | 96 (17)$^a$  | 131 (11)$^c$ | 2.8 (0.3)$^a$ | 4.0 (0.2)$^d$ | 21 (0.8)$^c$ | 20 (0.4)$^a$ |

(SD) standard deviation.

Materials labeled with similar letters in each column are not statistically different.
Table 3 summarizes the advantages and disadvantages identified in the materials investigated. Figure 3 shows the differences in the polymer structure of the materials after being treated with solvent THF. This Figure shows that SR Vivodent CAD had some phases which behaved differently by the solvent treatment whereas the others had homogeneous looking surface after being solvent treated.

**DISCUSSION**

The aim of this study was to investigate the mechanical properties of five CAD/CAM materials used for the fabrication of provisional restorations or digital denture teeth in terms of flexural strength, flexural modulus, surface microhardness, and bond strength under two different storage conditions. The results of the study supported the research hypothesis, which stated that, the differences in material type and storage conditions would significantly affect the evaluated mechanical properties. However, the materials’ differences did not seem to affect the bond strength of the materials investigated.

Interim restorations fabricated from industrially polymerized resins for CAD/CAM manufactured prostheses might be suitable to be used as long-term reconstructions. The reasoning lies on their superior mechanical properties and better marginal fit when compared with those fabricated manually. The use of these kinds of CAD/CAM materials for interim restorations also offers new treatment options as it is the case in complex treatments and immediate loading protocols. Long-term interim prostheses are commonly used for implant-supported treatments, as well as for periodontal therapy that requires extended follow-up and maxillofacial rehabilitations where the prostheses could be exposed to functional loading. Clinical studies have investigated the effect that the type of material has on the prosthetic complications’ rate. Some authors have reported this prosthetic complication rate for temporary restorations as 17.1% and less than 1% for definitive prostheses.

It was found in the current study that Zirkonzahn Temp Basic showed the lowest values for flexural strength, flexural modulus, and surface microhardness when tested dry or after 30 days water storage. This was in agreement with the findings reported by some authors when they evaluated the load-bearing capacities of resin-based fixed dental prostheses. They found that restorations fabricated from Zirkonzahn Temp
basic recorded the lowest values (280±87.3 N) and were not significantly different from those fabricated with conventional techniques. Therefore, this material might be suitable for short-term provisional restorations of up to six months as it is indicated by the manufacturer.

In the present in vitro study, SR Vivodent CAD recorded high values for flexural strength, flexural modulus, and surface hardness, which were not statistically significantly different from the other three materials (Zirkonzahn Multistratum flexible, Degos Dental L-Temp multicolor, and ZCAD™ Temp Esthetic) under dry conditions. This difference is most likely related to the different chemical composition of the materials investigated. This composition in the case of SR Vivodent CAD is a PMMA-based double cross-linked material, which means that the polymer filler and matrix are homogeneously cross-linked. The result is a thoroughly cross-linked material system, offering substantial advantages in terms of bond to denture base materials and improved mechanical properties.

L-Temp multicolor and ZCAD™ Temp Esthetic materials consist of a cross-linked PMMA which is known as interpenetrating polymer network (IPN) material which is produced by polymers of different chemical and physical natures that penetrate each other and become interlaced with the help of swelling processes. The glass transition temperature of regular non-cross linked PMMA is 125°C. Cross-linking increases the glass-transition temperature and hence the mechanical strength of the product. Additionally, it improves the material fracture resistance. This is in agreement with a study reported in the literature where higher flexural strength values were found for fixed partial dentures fabricated from a highly cross-linked PMMA when compared with those fabricated from a non-cross-linked material.

Surface hardness can predict the wear resistance of a material and its ability to abrade the opposing structure. Although Zirkonzahn Multistratum flexible recorded high values for flexural strength, their flexural modulus and surface hardness values were significantly lower than the other tested materials except for Zirkonzahn Temp basic. This might be attributed to its flexibility since Zirkonzahn Multistratum flexible
consists of a thermoplastic resin, which is a linear polymer without cross-linking agent as stated by the manufacturer. Interestingly, the THF solvent treatment test did not reveal dissolving of surface which may suggests that the polymer structure although it was linear (not cross-linked) was syndiotactic or isotactic providing better capability to resist effects by solvents.

Previous studies concluded that thermostatic resins with low modulus of elasticity and nanohardness were more liable to wear when compared with PMMA. In a previous study, significantly greater wear resistance was found on denture teeth fabricated from DCL material or highly cross-linked PMMA when compared to those made of conventional acrylic. The statistical analysis in this study showed that the storage condition had a significant effect on the tested parameters. Water storage significantly increased the flexural strength and flexural modulus of SR Vivodent CAD, Multistratum Flexible, and ZCAD Temp Esthetic. However, it significantly decreased their surface microhardness except for ZCAD Temp Esthetic. This was in agreement with the results of a study that compared the fracture strength of temporary fixed partial dentures fabricated from CAD/CAM versus directly fabricated restorations after water storage at 37°C for 3 months. They attributed that to the fact that CAD/CAM blocks are polymerized under optimal conditions, without the interference of water. During the water storage period of these blocks, post polymerization processes as well as relaxation phenomena may have occurred causing an improvement of the physical properties.

This study also found a non-significant difference in terms of bond strength between the groups investigated. A previous study did not find any connection between chemical composition (cross-linking agents or conventional PMMA) and bond strength of artificial teeth. Similar bonding characteristics of the tested materials is supported also by the findings of the THF solvent treatment test: The materials had similar behavior, which suggests that the bonding based on the surface dissolution (so-called secondary IPN bonding) do not considerably differ between the studied materials.

For implant-supported dental prostheses, firm primary implant stability, immediate splinting, and controlled occlusion are essential parameters for achieving successful clinical outcomes. Implant splinting with a rigid implant-supported bridge is thought to minimize transferring occlusal loads to the implants. Additionally, it can be beneficial in minimizing lateral forces on implants if more than 2 implants are involved. Therefore, based on the results of this study, SR Vivodent CAD, Harvest ZCAD Temp Esthetic, and Degos Dental L-Temp MC might be considered for constructing implant-retained provisional bridges as a first choice instead of Zirkonzahn Temp Basic and Zirkonzahn Multistratum Flexible.

The results of this study convey advice to clinicians in terms of selecting carefully CAD/CAM disks when planning interim fixed restorations because disks from different brands vary in strength. As static loads were applied in this study and results may be different when cyclic loads are used, the results of the current study should be elucidated accordingly. The results presented here should also allow clinicians to make comparisons among different systems concerning the performance of the tested materials under standardized conditions.

CONCLUSION

The tested materials showed variation in their flexural properties and surface microhardness whereas their bonding properties with resin luting cement were similar.

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REFERENCES

1) Balkenhol M, Ferger P, Mautner MC, Wöstmann B. Provisional crown and fixed partial denture materials: mechanical properties and degree of conversion. Dent Mater 2007; 23: 1574-1583.
2) Romano GE, Gaertner K, Nentwig GH. Long-term evaluation of immediately loaded implants in the edentulous mandible using fixed bridges and platform shifting. Clin Implant Dent Relat Res 2014; 16: 601-615.
3) Drago C. Frequency and type of prosthetic complications associated with interim, immediately loaded full-arch prostheses: A 2-year retrospective chart review. J Prosthodont 2016; 25: 433-439.
4) Maló P, Rangert B, Nobre M. ‘All-on-Four’ immediate-function concept with Bränemark System implants for completely edentulous mandibles: a retrospective clinical study. Clin Implant Dent Relat Res 2003; 1: 2-9.
5) Drago C. Accelerated treatment protocols: full arch treatment with interim and definitive prostheses. Gen Dent 2012; 60: 480-491.
6) Burns DR, Beck DA, Nelson SK, Committee on Research in Fixed Prosthodontics of the Academy of Fixed Prosthodontics. A review of selected dental literature on contemporary provisional fixed prosthodontic treatment: report of the Committee on Research in Fixed Prosthodontics of the Academy of Fixed Prosthodontics. J Prosthodent 2003; 90: 474-497.
7) Goldberg J, Ronaghi G, Phark JH, Jivraj S, Chee W. Force-to-failure of a simulated implant-supported complete fixed dental prosthesis reinforced with glass fiber. J Prosthodent 2017; 118: 172-176.
8) Gough M. A review of temporary crowns and bridges. Dent Update 1994; 21: 203-207.
9) Shor A, Schuler R, Goto Y. Indirect implant-supported fixed provisional restoration in the esthetic zone: fabrication technique and treatment workflow. J Esthet Restor Dent 2008; 20: 82-95.
10) Balkenhol M, Köhler H, Orbach K, Wöstmann B. Fracture toughness of cross-linked and non-cross-linked temporary crown and fixed partial denture materials. Dent Mater 2009; 25: 917-928.
11) Lodding DW. Long-term esthetic provisional restorations in dentistry. Curr Opin Cosmet Dent 1997; 4: 16-21.
12) Fürhauser R, Mailath-Pokorny G, Haas R, Busenlechner D, Watzek G, Fommer B. Immediate restoration of immediate
implants in the esthetic zone of the maxilla via the copy-abutment technique: 5-year follow-up of pink esthetic scores. Clin Implant Dent Relat Res 2017; 19: 28-37.

13) Small BW. Indirect provisional restorations. Gen Dent 1999; 47: 140-142.

14) McLean JW. The failed restoration: causes of failure and how to prevent them. Int Dent J 1990; 40: 354-358.

15) Aghardt E, Panigatti S, Cleriço M, Villa C, Maló P. Immediate rehabilitation of the edentulous jaws with full fixed prostheses supported by four implants: interim results of a single cohort prospective study. Clin Oral Implants Res 2010; 21: 459-465.

16) Rayyan MM, Aboushebl M, Sayed NM, Ibrahim A, Jimbo R. Comparison of interim restorations fabricated by CAD/CAM with those fabricated manually. J Prosthet Dent 2015; 114: 414-419.

17) Nohrström TJ, Vallittu PK, Yli-Urho A. The effect of placement and quantity of glass fibers on the fracture resistance of interim fixed partial dentures. Int J Prosthodont 2000; 13: 72-78.

18) Edelhoff D, Beuer F, Schweiger J, Brix O, Stimmelmayer M, Guth JF. CAD/CAM-generated high-density polymer restorations for the pretreatment of complex cases: a case report. Quintessence Int 2012; 43: 457-467.

19) Stawarczyk B, Liebermann A, Eichberger M, Guth JF. Evaluation of mechanical and optical behavior of current esthetic dental restorative CAD/CAM composites. J Mech Behav Biomed Mater 2015; 55: 1-11.

20) Alt V, Hannig M, Wöstmann B, Balkenhol M. Fracture strength of temporary fixed partial dentures: CAD/CAM versus directly fabricated restorations. Dent Mater 2011; 27: 339-347.

21) Göncü Başaran E, Ayna E, Vallittu PK, Lassila LVJ. Load-bearing capacity of handmade and computer-aided design —computer-aided manufacturing-fabricated three-unit fixed dentures of particulate filler composite. Acta Odontol Scand 2011; 69: 144-150.

22) Potinay DJ, Klüm J. CAD/CAM in-office technology: innovations after 25 years for predictable, esthetic outcomes. J Am Dent Assoc 2010; 141: 55-95.

23) Stawarczyk B, Ender A, Trottmann A, Özcan M, Fischer J, Hämmerle CHF. Load-bearing capacity of CAD/CAM milled polymeric three-unit fixed dental prostheses: effect of aging regimens. Clin Oral Investig 2012; 16: 1699-1677.

24) Gougaloff R, Stalley FC. Immediate placement and provisionalization of a dental implant utilizing the CEREC 3 CAD/CAM Protocol: a clinical case report. J Calif Dent Assoc 2010; 38: 170-173, 176-177.

25) Güt JF, Almeida E, Silva JS, Beuer F, Edelhoff D. Enhancing the predictability of complex rehabilitation with a removable CAD/CAM-fabricated long-term provisional prosthesis: a clinical report. J Prosthet Dent 2012; 107: 1-6.

26) Vallittu PK. The effect of glass fiber reinforcement on the fracture resistance of a provisional fixed partial denture. J Prosthet Dent 1998; 79: 125-130.

27) Haselton DR, Díaz-Arnold AM, Vargas MA. Flexural strength of provisional crown and fixed partial denture resins. J Prosthet Dent 2002; 87: 225-228.

28) Prousseaefs P. Immediate provisionalization with a CAD/CAM interim abutment and crown: a guided soft tissue healing technique. J Prosthet Dent 2015; 113: 91-95.

29) Drago C. Cantilever lengths and anterior-posterior spreads of interim, acrylic resin, full-arch screw-retained prostheses and their relationship to prosthetic complications. J Prosthodont 2017; 26: 502-507.

30) Drago C. Ratios of cantilever lengths and anterior-posterior spreads of definitive hybrid full-arch, screw-retained prostheses: results of a clinical study. J Prosthodont 2018; 27: 402-408.

31) Cekic-Nagas I, Egilmez F, Ergun G, Vallittu PK, Lassila LVJ. Load-bearing capacity of novel resin-based fixed dental prosthesis materials. Dent Mater J 2018; 37: 49-58.

32) Yilmaz B. CAD-CAM high-density polymer implant-supported fixed diagnostic prostheses. J Prosthodont 2018; 11: 688-692.

33) Kumar P, Choona NA, du Toit LC, Pillay V. Advances in patented interpenetrating polymeric networks for biomedical applications. Pharm Pat Anal 2018; 7: 99-101.

34) Klempner D. Advances in interpenetrating polymeric networks —Google Scholar [Internet]. [cited 2019 Jan 3]. Available from: https://scholar.google.com/scholar_lookup?hl=en&publication_year=1999&pages=1-290&author=D+Klempner&title=Advances+in+Interpenetrating+Polymer+Networks

35) Anusavice KJ. Phillips’ science of dental materials - Google Scholar [Internet]. [cited 2019 Jan 3]. Available from: https://scholar.google.com/scholar_lookup?hl=en&publication_year=2017&pages=1-140&author=K.J.+Anusavice&author=K.J.+Anusavice&author=K.J.+Anusavice

36) Suzuki T, Takahashi H, Arksornnukit M, Oda N, Hirano S. Bonding Properties of heat-polymerized denture base resin to Ti-6Al-7Nb alloy. Dent Mater J 2005; 24: 530-535.

37) Fajardo RS, Pruitt LA, Finzen FC, Marshall GW, Singh S, Singh S, et al. The effect of E-glass fibers and acrylic resin thickness on fracture load in a simulated implant-supported overdenture prosthesis. J Prosthodont 2011; 106: 373-377.

38) Nasution H, Kamonkantikul K, Arksornnukit M, Takahashi H. Pressure transmission area and maximum pressure transmission of different thermoplastic resin denture base materials under impact load. J Prosthodont Res 2018; 62: 44-49.

39) Basavarajappa S, Al-Kheraif AA, ElSharawy M, Vallittu PK. Effect of solvent/disinfectant ethanol on the microsurface structure and properties of multiphase denture base polymers. J Mech Behav Biomed Mater 2016; 54: 1-7.

40) Basavarajappa S, Abdullah Alkheraif AA, Alhijji SM, Matinlinna JP, Vallittu PK. Effect of ethanol treatment on mechanical properties of heat-polymerized polymethyl methacrylate denture base polymer. Dent Mater J 2017; 36: 834-841.

41) Ruyter IE. Methacrylate-based polymeric dental materials: conversion and related properties. Summary and review. Acta Odontol Scand 1982; 40: 359-376.

42) Hamanaka I, Iwamoto M, Lassila LVJ, Vallittu PK, Takahashi Y. Wear resistance of injection-molded thermoplastic denture base resins. Acta Biomater Odontol Scand 2016; 2: 31-37.

43) Suzuki S. In vitro wear of nano-composite denture teeth. J Prosthodont 2004; 13: 238-243.

44) Chai J, Takahashi Y, Takahashi T, Habu T. Bonding durability of conventional resinous denture teeth and highly crosslinked denture teeth to a pour-type denture base resin. Int J Prosthodont 2000; 13: 112-116.

45) Vallittu P, Matinlinna J. Types of FRCs used in dentistry. Dent Mater J 2018; 37: 49-58.