Dentistry 3000

Vol 13 No 1 (2025) DOI 10.5195/d3000.2025.877

Mechanical Characteristics of Teeth Restored with Innovative Functionally Graded Posts Made of Titanium-Hydroxyapatite-Bioactive Glass

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Abstract

Objectives: Novel functionally graded dental posts were fabricated, and their mechanical properties were evaluated and then compared with three different commercially dental posts.

Materials and Methods: The FGDPs were fabricated by sintering various ratios of bioactive glass (BG), hydroxyapatite (HA), and titanium (Ti) at 900ºC in air atmosphere. Four groups of forty maxillary central incisors were selected, and each group restored with titanium, stainless steel, fiber, or FGDPs. To analyze stress distribution and assess fracture resistance and failure mechanisms, four finite element models of teeth repaired with FGDP, fiber, titanium, and stainless-steel posts, respectively, were created.

Results: The fracture resistance of teeth repaired using FGDPs was greater (mean = 550 ± 72 N) compared with those restored with titanium (mean = 505 ± 58 N), fibre (mean = 475 ± 70 N) and stainless steel (mean = 422 ± 58 N) posts. Statistical analysis showed a significant difference between FGDPs and stainless-steel posts (p = 0.000). When FGDP-restored teeth contrasted with those who had fibber, titanium and stainless-steel posts were 70%, 50%, and 40 %, respectively, of restorable failures (RF), and 100% occurred in the former group.

Conclusions: Comparing the FGDP and fibre models to the pothers, finite element analysis IFEA) reveled that stress was distributed more frequently throughout them. It is evident that when FGDPs made using the Ti-HA-BG technology was compared to other dental posts that are sold commercially, they functioned better as dental posts.

Keywords: Dental Materials; Dental Posts; Resistance to Fractures; Material Failure; Stress.

Citation: Abdulmunem M, et al. (2025) Mechanical Characteristics of Teeth Restored with Innovative Functionally Graded Posts Made of Titanium-Hydroxyapatite-Bioactive Glass. Dentistry 3000. 1:a001 doi:10.5195/d3000.2025.877
Received: March 9, 2025
Accepted: April 10, 2025
Published: May 6, 2025

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Introduction

The topic of root canal therapy has been extensively researched. Human teeth typically lose their structure and integrity because of several conditions, including dental caries, trauma, and even root canal therapy. When teeth are loaded or masticated, all these variables might weaken them and increase the risk of fractures [1,2]. After receiving a root canal therapy to preserve the remaining tooth structure and prevent tooth loss, a coronal restoration is placed in place [3]. If there is significant damage to the tooth structure that prevents the coronal restorations from being retained, a dental post must be inserted for repairing endodontically treated teeth. Dental posts have therefore established themselves as the preferred course of therapy [4-6]. Numerous post varieties, including those made of titanium, fiber, zirconium, and stainless steel, offer

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excellent strength, toughness, and fracture resistance. They do, however, have drawbacks, including loss of retention, difficulty retrieving, and creation of irreversible failures [5,7]. As a result of the uniform material used to make all commercial posts, it is more difficult to disperse stress under force, increasing the risk of irreversible failures. Accordingly, a functionally graded approach based on Ti-HA materials is taken into consideration in addition to post kinds [8-10].

Three different kinds of functionally graded dental posts (FGDp) were created in 2011 by Abu Kasim et al. using ZrO2-Ti-HA, Al2O3-Ti-HA, and Ti-HA materials [8]. Four layers made up these dental posts, which allowed the tension to be evenly distributed from the post to the dentine. Because of their increased ability to endure forces exerted during loading and mastication, the teeth had more RF [8].

It is commonly recognized that the chemical and crystallographic structures of hydroxyapatite and bone mineral are comparable. Since hydroxyapatite is biocompatible with human bone, it is frequently utilized in dentistry and medical procedures [11-13]. Unfortunately, it is weak and fragile [14,15]. Titanium is employed in numerous medicinal applications and has superior mechanical qualities than HA. When compared to HA, it is less biocompatible, however [16-19]. Dehydration and HA degradation are common during the high temperature sintering of Ti/HA [20]. Because it may increase HA's biocompatibility and solve the sintering temperature issue, bioactive glass (BG) may be a promising option for sintering hydroxyapatite-titanium composites [20-22].

To provide root canal treated teeth greater mechanical qualities, functionally graded dental posts, or FGDPs, were created for this study. They also have higher restorable failure rates, which is thought to improve the teeth's resistance to fracture by increasing stress distribution during loading. Until far, no research has been done on the synthesis of Ti-HA, FGDP combined with bioactive glass materials. The purpose of the study was to lower the sintering temperature and prevent any potential issues by adding bioactive glass to Ti-HA FGDP. The present investigation was a component of a larger research including two sections. The first section examined and assessed the impact of bioactive glass and sintering conditions on individual Ti-HA separated composites (layers) [23].

Following their fabrication, the endodontically treated teeth were repaired using FGDP made of Ti-HA-BG materials. Consequently, three different types of commercially available dental posts (made of various materials) were used to restore teeth, and their mechanical characteristics were investigated and compared with those of the reconstructed teeth. Furthermore, the stress distributions of the manufactured FGDP were analyzed using a finite element method in comparison to other dental post kinds.

Material and Methods

Fabrication of the functionally graded dental post

The FGDPs has five layers at which the top layer is mostly contain Ti and the bottom layer is HA rich, and 10% BG was added to all the layers (fabrication of each layer was discussed in part 1 of this project by Abdulmunem *et al.,* 2021 [21]. BG was formed by milling eight different materials: SiO_2, NaO, CaO, P_2O_5, B_2O_3, TiO_2, CaF_2, and MgO together using a planetary ball milling machine (2 x 10^2 rpm/ five hrs.).

Utilizing silicone impression materials (Aquasil, Dentsply, Konstanz, Germany), molds were created. Beginning with layer 1 and

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going through layer 5, layers of Ti-HA-BG powders were poured into the molds, and the layers were sealed using the same methods used for the imprint. After that, the samples were compressed at 250 MPa using a cold isostatic press. The samples were then sintered at 9 x10^2 Ċ in an atmosphere furnace. The samples were heated to 500 Ċ for 240 minutes after being at room temperature and remain in same level. The samples were cooled for eight hours overnight after the temperature was progressively increased with 240 min to 9 x 10^2 Ċ and maintained at same level for an additional 240 minutes. Samples were subsequently transported to a centerless grinder (Palmary PC-12S-NC, Taiwan) for shaping and machining to create FGDPs with the necessary diameter of 1.5 mm.

Root canal treatment and post-space preparation

A total of forty removed human maxillary central incisors that were free of cavities, cracks, and prior endodontic treatments were chosen (DF RD 1411/0058(P) is the reference number for the ethics committee/IRB). The cementum-enamel junction (CEJ) of every tooth was measured at 16 mm from the apex. A straight hand piece was used to segment the remaining crowns using a diamond disc. The step-back approach was employed in the instrumentation process. The master file was identified as a 45 K-file, and each of these files had a working length of 14 mm.

Rattana (Dentsply/Asia, Hong Kong, China), AH-plus (Dentsply DeTrey, Germany), a resin-based sealer, and the lateral compaction method were used for root canal fills. Following that, size 3 gates-glidden drills were used to remove 9 mm of gutta-percha. Once the post area was ready, special drills matching each post's operating length of 9 mm were employed. Subsequently, all roots were combined into blocks of epoxy resin.

Organizing samples and assessing fracture resistance and failure mechanism

Four groups of ten roots were formed. The diameter of each post was 1.5 mm and its length was 14 mm. Group 2 received titanium posts (Para Post XP, Coltene/Whaledent, USA) for root restoration, whereas Group 1 received FGDPs for root restoration. Para Post Fibre Lux, Coltene/Whaledent, USA, was used to repair the roots in group 3, and Para Post XP, Coltene/Whaledent, USA, was used to restore the roots in group 4. Zinc phosphate cement was used to bond each post in the root canals. After that, metal copings were used to keep the composite cores in place over all the posts and roots. To load each sample at a 45-degree angle plane to its long axis, it was positioned in a unique jig that was attached to a Shimadzu universal testing machine. Two millimeters below the metal copings' incisal edge, a crosshead pin was inserted at a pace of 0.5 mm/min until failure.

Data analysis

All data were statistically analyzed using the One-Way ANOVA at *p*= 0.05, and pair-wise comparisons were done using both Tukey and chi-square tests. The failure modes of each sample were investigated using the chi-square test, and the samples were thereafter sent to be examined for fractures using a 20 X stereomicroscope (SZ X7, Olympus, Japan).

Finite element modelling

A finite element model was built to examine the stress distribution among the various posts. Solid works software (Dassault Systèmes SolidWorks Corporation) was used to create four models that approximated human maxillary central incisors. The first model was developed with FGDP, the second model with a fiber post, the third model with a stainless-steel post, and the fourth model with a

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titanium post. Each model has a different type of post.

Stress distribution was calculated using the SolidWorks/surface modelling (Version premium 2015, Dassault Systèmes, USA). Loads were applied to the four models in three directions (vertical, horizontal and oblique) at 100 N to simulate the masticatory force, external traumatic force and bruxism [24,25]. Different post types were used to construct each model: FGDP was used to develop the first model, fibre posts were used to establish the second model, stainless steel posts were used to establish the third model, and titanium posts were used to establish the fourth model.

Results

Evaluation of fracture resistance and failure mode

Figure 1 shows the mean and standard deviation of the dental post groups. By using a post-hoc (Tukey test) test for multiple comparisons, a one-way ANOVA was utilized to ascertain if there was a significant difference between the dental post groups (Table 1). The fracture resistance values of the FGDPs group mean were (550 ± 72) that were greater than the titanium, fiber, and stainless-steel groups (505 ± 58), (475 ± 70), (422 ± 58) respectively.

The evaluated dental post groups differed considerably from one another, with the FGDP group's teeth exhibiting much stronger fracture resistance than the stainless-steel group's ($p = 0.000$). Additionally, compared to teeth in the stainless-steel group, those in the titanium group exhibited greater fracture resistance ($p = 0.032$). The teeth in the titanium, fiber, and FGDP groups did not differ significantly from one another. Table 2 indicates the quantity and proportion of failure mechanisms. Ten RF have been filed in teeth repaired with FGDPs, then seven RF in teeth restored with fiber, five RF in titanium, and four RF in stainless steel roots. As the fracture line is 2 mm below the cementum-enamel junction (CEJ) and above the epoxy resin block line, Figure 2a depicts the restorable failure pattern of teeth in the FGDP group. The fiber group's restorable failure is depicted in Figure 2b. Additionally, the fracture began obliquely and finished with a 2 mm horizontal line that was above the epoxy resin block line and below the CEJ. The titanium group's non-RF fractures are seen in Figure 2c, where they extend past the epoxy resin block line to the middle third of the root. On the other hand, Figure 2d depicts the non-restorable failure mode of the stainless-steel group, in which the fracture line extended below the epoxy resin block line and began obliquely.

Finite element analysis

Stress distribution under vertical load

Figure 3a shows the stress distribution of all FE models under vertical load. In the FGDP and fiber models, compared to the other models, there was significantly less force applied to the root's cervical third, and the apical third of the root received very little stress. Notably, the FGDP model's apical third showed the least amount of tension, but the post's coronal and middle third showed no stress at all.

Apart from the core-crown contact, the titanium and stainless-steel models also displayed greatest pressures in the apical third of the post-root interfaces, leading to the non-RF. The coronal and middle thirds of the posts of the titanium and stainless-steel versions had the least amount of stress, whereas the apical third of the posts had the most stress.

Stress distribution under oblique load

The titanium, FGDP, and fiber models had the highest levels of stress under the oblique load direction (Figure 3b), in that order. At the contacts between the

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coronal third of the crowns and the core, the stress was focused. The middle third and cervical regions of the root received less stress. According to the FGDP model, the root structure received a homogeneous distribution of stress, with very little stress dispersion along the post. The stress was centered at the core-crown contact. Less stress was placed on the cervical and middle thirds of the root in the titanium and stainless steel models, whereas the most stress was localized at the coronal third of the crown's core-crown contacts. Less stress was observed at the coronal third of the titanium post, whereas a small pit formed at the apical third of the post.

Stress distribution under horizontal load

Maximum stress was displayed in the titanium and FGDP models relative to the other models for the horizontal loading (Figure 3c). The contact between the core, root, and crown displayed stress distribution in the titanium and FGDP models. The coronal third of the crown-core interface's core-crown interaction was the site of the greatest stress. The titanium post's midsection experienced less stress, and its apical stress also dropped. There was no stress seen at the apical third of the post and very little tension observed at the intersection of the coronal and middle third of the post along the FGDP surfaces. The coronal third of the crown's core-crown contact was where the greatest concentrations of stress were found in the fiber and stainless-steel models, but the cervical third of the root's crown-root interface showed minimal stress. The stainless steel and fiber versions' post surfaces were free of tension.

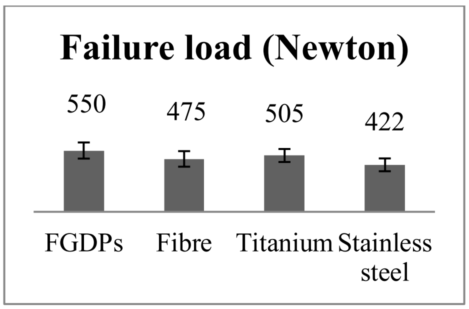

Figure 1. Means and standard deviations of fracture resistance the dental post groups.

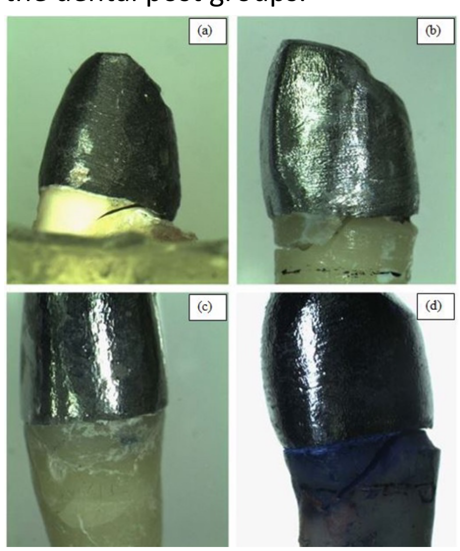

Figure 2. Representative image of (a) restorable failure of FGDPs group; (b) restorable failure of fiber group; (c) non-restorable failure of titanium group; and (d) non-restorable failure of stainless-steel group.

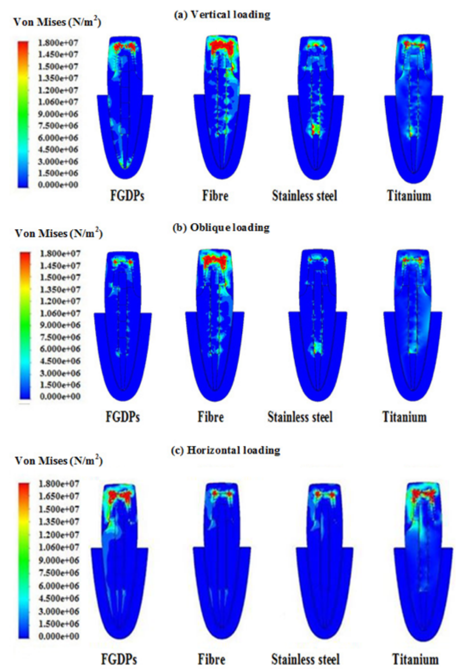

Figure 3. Stress distribution under vertical (a), oblique (b), and horizontal (c) loadings for different tooth models.

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Table 1. Multiple comparisons of the fracture resistance between the dental post groups.

Type of post (I)	Type of post (J)	Mean Difference (I-J)	Standard Error	*P*-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Titanium	Fibre	30.70000	29.0232	0.717	-47.4663	108.8663
	Stainless steel	83.70000	29.0232	0.032	5.5337	161.8663
	FGDPs	-44.70300	29.0232	0.425	-122.8693	33.4633
Fiber	Titanium	-30.70000	29.0232	0.717	-108.8663	47.4663
	Stainless steel	53.00000	29.0232	0.278	-25.1663	131.1663
	FGDPs	-75.40300	29.0232	0.062	-153.5693	2.7633
Stainless-steel	Titanium	-83.70000	29.0232	0.032	-161.8663	-5.5337
	Fibre	-53.00000	29.0237	0.278	-131.1663	25.1663
	FGDPs	-128.40300	29.0237	0.000	-206.5693	-50.2367
FGDPs	Titanium	44.70300	29.0237	0.425	-33.4633	122.8693
	Fibre	75.40300	29.0237	0.062	-2.7633	153.5693
	Stainless steel	128.40300	29.0237	0.000	50.2367	206.5693

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Table 2. Number and percentages of failure modes of the dental post groups.

Type of dental post	n	Failure mode	
		Restorable	Non-restorable
FGDPs	10	10 (100%)	0 (0%)
Fiber	10	7 (70%)	3 (30%)
Titanium	10	5 (50%)	5 (50%)
Stainless steel	10	4 (40%)	6 (60%)

Discussion

In this study, bioactive glass was added to Ti-HA FGDPs to aid in the sintering process. FGDPs were produced in this study to provide a regular stress distribution for root canal treated teeth and thus improve the fracture resistance and increase the susceptibility of reparable failures [23]. According to the results of the current study, teeth repaired with titanium posts and FGDPs were more fracture resistant than teeth treated with stainless steel posts. These findings are consistent with studies that looked at the fracture resistance of teeth repaired using other FGDP formulations, including ZrO2-Ti-HA, Al2O3-Ti-HA, and Ti-HA-Ti, as well as other teeth treated using cast and titanium posts [10]. A dental post that is fabricated using the functionally graded concept—which calls for more stiffness at the coronal and less stiffness at the apical parts of the post—will have an elastic modulus that is like dentine's and will aid in progressively lowering stresses on the apical third of the root. This will strengthen the tooth's resistance to fracture and help it withstand stresses applied while it functions [8,9,23].

The first layer of the FGDP, which was kept in the core materials, had an elasticity modulus of 20248 MPa, whereas the second layer had an elasticity modulus of 17939 MPa, as seen in Figure 3. According to Dejack [26], these numbers are rather near to the dentine's 18600 MPa density. The fourth and fifth layers' moduli of elasticity were measured to be 8766 MPa and 7147 MPa, respectively. As a result, stress was distributed coronally and decreased apically, increasing the tooth's resistance to fractures, as was covered in Section 4.4 and supported by several studies [8,10].

Regarding failure mechanisms, the teeth repaired with FGDPs (10 RF) failed with more frequency in this study than teeth restored with fiber (7 RF), titanium (5 RF), and stainless steel (four RF) dental posts.

Researchers found that as compared to teeth repaired with cast and titanium posts, teeth treated using FGDPs (based on ZrO2-Ti-HA, Al2O3-Ti-HA, and Ti-HA-Ti) tended to fail with higher radiofrequency. The titanium, cast post, and core groups all experienced catastrophic failures; just one tooth from each group failed with RF, while the majority of

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the teeth failed with non-RF. Conversely, teeth that were repaired using all three kinds of FGDPs displayed between 80% and 90% of RF [10] .

From the coronal to the apical third of the dental post, the functionally graded multi-layered composition of the dental posts saw progressive variations in stiffness. A restorable failure was caused by layers with lesser stiffness spreading the stress to the neighbouring root structures in a regular pattern, whereas layers with high stiffness (at the coronal third) removed the stress from the core [8,23]. Additionally, the modulus of elasticity is relevant. The coronal sections of the manufactured FGDPs in this investigation had a greater modulus of elasticity than the apical regions. As a result, stress was focused on the coronal region of the FGDPs at the post-core interface. Problems centered in the coronal region [8].

Non-RF can result from the restoration of endodontically treated teeth with a high modulus of elasticity and homogeneous dental posts, such titanium and stainless-steel posts, which will unevenly distribute stress on the root systems [27]. During the apical third of post-root contacts in the current study, the titanium and stainless-steel models showed higher maximum stress concentrations than the fiber and FGDP models. Throughout its long axis, the dental post should retain a distinct and progressive modulus of elasticity to prevent uneven stress distribution from the post to the tooth tissues.

To offer superior retention for the cores, the coronal third of the post should have a larger modulus of elasticity than the other post thirds. To minimize stress and minimize the likelihood of non-RF, the modulus of elasticity should be supplied consistently to the root structures and progressively lowered towards the apical third. As demonstrated in this work, where layers 1 and 2 exhibited greater levels of modulus of elasticity compared with layers 3, 4, and 5, this may be accomplished by creating dental posts with functionally graded compositions [8-10]. (Fig. 3).

In this investigation, the FGDP model performed better in terms of stress distribution than the titanium and stainless-steel models. In this study, models loaded in a vertical direction exhibited a higher concentration of stress than models loaded in an oblique or horizontal manner. This result contradicts a prior study's conclusion that models loaded in a vertical direction showed a higher maximum stress than those placed in a horizontal orientation [28]. That may be because the study's post designs and diameters differed from models that employed typical 1.5 mm diameter posts with parallel-sided post designs.

The FGDPs used in this study have therapeutic consequences since they give root canal treated teeth a regular stress distribution, which raises the risk of RF and lowers the chance of having to remove a tooth when a failure occurs.

Conclusion

The limitation of this study was using the static compressive load instead of cyclic load and thus fatigue was not simulated in this study. Moreover, no *in vivo* tests were done, and only *in vitro* tests were performed in this study. Therefore, loading teeth under cyclic load and performing *in vivo* tests in future studies are recommended.

This study has shown teeth restored with FGDPs have better mechanical properties compared with those restored with homogenous dental posts. The gradual change in modulus of elasticity of functionally graded dental posts improved stress distribution, fracture resistance and failure mode of teeth restored

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with FGDPs. Therefore, this study suggests FGDPs based on Ti-HA-BG materials can be used as restoration material of choice for endodontically-treated teeth.

Acknowledgement

This research was supported by the FRGS No. FP019-2017A grant, from the Faculty of Dentistry, University of Malaya, Kuala Lumpur, Malaysia.

Conflicts of interest

The authors have no conflicts of interest to declare.

References

1. Krishan, R., et al., *Impacts of conservative endodontic cavity on root canal instrumentation efficacy and resistance to fracture assessed in incisors, premolars, and molars.* Journal of endodontics, 2014. **40**(8): p. 1160-1166.
2. de V Habekost, L., et al., *Fracture resistance of thermal cycled and endodontically treated premolars with adhesive restorations.* The Journal of prosthetic dentistry, 2007. **98**(3): p. 186-192.
3. Bachicha, W.S., et al., *Microleakage of endodontically treated teeth restored with posts.* Journal of Endodontics, 1998. **24**(11): p. 703-708.
4. Aurélio, I., et al., *Are posts necessary for the restoration of root filled teeth with limited tissue loss? A structured review of laboratory and clinical studies.* International endodontic journal, 2016. **49**(9): p. 827-835.
5. Mahmoudi, M., et al., *Influence of inhomogeneous dental posts on stress distribution in tooth root and interfaces: Three-dimensional finite element analysis.* Journal of Prosthetic Dentistry, 2017. **118**(6): p. 742-751.
6. Abdulmunem, M., et al., *The combined effect of dental post and cement materials on fracture resistance and fracture mode of endodontically-treated teeth.* Sains Malaysiana, 2015. **44**(8): p. 1189-1194.
7. Schwartz, R.S. and J.W. Robbins, *Post placement and restoration of endodontically treated teeth: a literature review.* Journal of endodontics, 2004. **30**(5): p. 289-301.
8. Abu Kasim, N.H., et al., *3D-FE analysis of functionally graded structured dental posts.* Dental materials journal, 2011. **30**(6): p. 869-880.
9. Dabbagh, A., et al., *Thermomechanical advantages of functionally graded dental posts: A finite element analysis.* Mechanics of Advanced Materials and Structures, 2017: p. 1-10.
10. Madfa, A.A., *Development of functionally graded composite for fabrication of dental post*. 2011, University of Malaya: Malaysia.
11. Ramesh, S., et al., *Characterization of biogenic hydroxyapatite derived from animal bones for biomedical applications.* Ceramics International, 2018. **44**(9): p. 10525-10530.
12. Zhou, S., et al., *The porous structure and mechanical properties of injection molded HA/PA66 scaffolds.* International Polymer Processing, 2014. **29**(4): p. 454-460.
13. Pei, D., et al., *Influence of nano-hydroxyapatite containing desensitizing toothpastes on the sealing ability of dentinal tubules and bonding performance of self-etch adhesives.* Journal of the mechanical behavior of biomedical materials, 2019. **91**: p. 38-44.
14. Veljović, D., et al., *The effect of the shape and size of the pores on the mechanical properties of porous HAP-based bioceramics.* Ceramics International, 2011. **37**(2): p. 471-479.
15. Mendelson, B.C., et al., *The fate of porous hydroxyapatite granules used in facial skeletal augmentation.* Aesthetic plastic surgery, 2010. **34**(4): p. 455-461.

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Vol 13 No 1 (2025) DOI 10.5195/d3000.2025.877

16. Li, Y.-H., F. Wang, and J.-J. Li, *Current developments of biomedical porous Ti–Mo alloys.* International Journal of Materials Research, 2017. **108**(8): p. 619-624.
17. Arifin, A., et al., *Material processing of hydroxyapatite and titanium alloy (HA/Ti) composite as implant materials using powder metallurgy: a review.* Materials & Design, 2014. **55**: p. 165-175.
18. Zhao, D., et al., *Effect of pore geometry on the fatigue properties and cell affinity of porous titanium scaffolds fabricated by selective laser melting.* Journal of the mechanical behavior of biomedical materials, 2018. **88**: p. 478-487.
19. Fathyunes, L., J. Khalil-Allafi, and M. Moosavifar, *Development of graphene oxide/calcium phosphate coating by pulse electrodeposition on anodized titanium: Biocorrosion and mechanical behavior.* Journal of the mechanical behavior of biomedical materials, 2019. **90**: p. 575-586.
20. Ning, C. and Y. Zhou, *On the microstructure of biocomposites sintered from Ti, HA and bioactive glass.* Biomaterials, 2004. **25**(17): p. 3379-3387.
21. Moskalenko, V. and A. Smirnov, *Temperature effect on formation of reorientation bands in α-Ti.* Materials Science and Engineering: A, 1998. **246**(1-2): p. 282-288.
22. Prasad, S., et al., *Crystallization and mechanical properties of (45s5-ha) biocomposite for biomedical implantation.* Ceramics–Silikáty, 2017. **61**(4): p. 378-384.
23. Abdulmunem, M., et al., *The Effect of Bioactive Glass and Sintering Conditions on the Properties of Titanium-Hydroxyapatite Composites.* Sains Malaysiana, 2021. **50**(4): p. 1089-1099.
24. Joshi, S., et al., *Mechanical performance of endodontically treated teeth.* Finite elements in analysis and design, 2001. **37**(8): p. 587-601.
25. Genovese, K., L. Lamberti, and C. Pappalettere, *Finite element analysis of a new customized composite post system for endodontically treated teeth.* Journal of Biomechanics, 2005. **38**(12): p. 2375-2389.
26. Dejak, B., A. Młotkowski, and C. Langot, *Three-dimensional finite element analysis of molars with thin-walled prosthetic crowns made of various materials.* Dental materials, 2012. **28**(4): p. 433-441.
27. Abdulmunem, M., et al., *Evaluation of the effect of dental cements on fracture resistance and fracture mode of teeth restored with various dental posts: A finite element analysis.* Journal of the European Ceramic Society, 2016.
28. Al-Omiri, M.K., M.R. Rayyan, and O. Abu-Hammad, *Stress analysis of endodontically treated teeth restored with post-retained crowns: A finite element analysis study.* The Journal of the American Dental Association, 2011. **142**(3): p. 289-300.