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**Evaluation Of Thermocycling, Color Stability, Surface Roughness And Hardness of
Nanocarbon HPP, BioHPP and PEEK Used For Fabrication Of Prosthetic Restorations
(In Vitro Study)**

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ABSTRACT

Statement of problem: The selection of appropriate dental materials plays a crucial role in the success of prosthetic restorations. With the limitations of metallic alloys, including their aesthetic shortcomings, weight, corrosion potential, and cost, there is growing interest in high-performance polymer alternatives.

Purpose: The objective of the present study was to evaluate color stability, surface roughness and Hardness of BioHPP, Nanocarbon HPP and PEEK used for fabrication of prosthetic restorations (An In Vitro Study).

Material and Methods: A total of 42 cylindrical samples (14 per group) were divided into three groups: Group 1: nanocarbon High-Performance Polymer, Group 2: BioHPP, Group 3: PEEK. They were fabricated using CAD/CAM technology and subjected to thermocyclic aging. Color stability was assessed spectrophotometrically after immersion in a staining medium over 28 days. Surface roughness was measured using a profilometer, while hardness was evaluated using the Vickers hardness test.

Results: Statistically significant differences were observed among all three materials in color stability, surface roughness, and hardness ($p < 0.001$). PEEK demonstrated the highest surface roughness, while nano-carbon reinforced polymer exhibited the lowest surface roughness and highest hardness values. In terms of color stability, all materials showed varying degrees of discoloration over time, but nano-carbon-HPP generally maintained better stability.

Conclusion: Nano-carbon-HPP demonstrated superior mechanical performance, combining low surface roughness with high hardness, making them a promising alternative to traditional materials for full-arch dental prostheses. These findings highlight the potential of nano-carbon materials to improve durability, patient comfort, and aesthetic outcomes in prosthodontic applications.

CLINICAL IMPLICATION: The use of nano-carbon reinforced polymers may improve the longevity, esthetics, and patient comfort of implant-supported overdentures.

KEYWORDS: BioHPP; PEEK; Nano-Carbon-HPP; Implant Overdenture; Surface Roughness; Hardness; Color Stability.

INTRODUCTION

While the prosthetic rehabilitation of total edentulism remains a cornerstone of restorative practice, managing the severely atrophic mandible presents a formidable clinical hurdle. This complexity is frequently exacerbated in the geriatric population, where advanced ridge resorption intersects with a diminished neuromuscular capacity to adapt to new prostheses. [1]

Integrating dental implants into the overdenture design addresses the primary shortcomings of conventional removable prosthodontics. This modality effectively arrests mandibular bone loss and optimizes bolus processing during mastication, translating to superior patient-reported outcomes and a higher degree of physiological well-being. [2]

Material selection is a critical determinant of long-term success, as the inherent mechanical properties of the restorative medium govern the transmission of occlusal forces to the peri-implant architecture. Specifically, the elastic modulus of the material dictates the stress distribution patterns within the implant-bone interface; contrary to some intuitive assumptions, current literature suggests that more compliant (less rigid) materials may precipitate higher stress concentrations in prosthetic components and the underlying bone complex due to increased flexural deformation.

The integration of metallic frameworks in implant prosthodontics serves as a strategic reinforcement to optimize the assembly's flexural rigidity. By establishing a rigid splinting effect across the implants, these frameworks mitigate the risk of catastrophic material failure while facilitating a more homogenous distribution of occlusal loads. Prevailing biomechanical

theory suggests that high-modulus materials minimize localized strain at the abutment-implant interface, thereby safeguarding the structural integrity of the prosthetic complex [3].

While metallic reinforcements provide high rigidity, they are increasingly scrutinized for their lack of adaptability and poor esthetic integration. The high density of these materials translates into a heavy prosthetic profile that can diminish the wearer's experience, particularly in extensive FP2 and FP3 reconstructions. Moreover, the risk of marginal mucosal discoloration and the significant fiscal overhead associated with alloy fabrication present ongoing challenges. These factors, alongside the difficulty of chairside adjustability, underscore the need for restorative materials that better balance biomechanical strength with biological and esthetic harmony [4]

The dental field is currently navigating a significant transition. For decades, metal alloys served as the undisputed benchmark against which all emerging materials were measured. However, the rapid maturation of CAD-CAM ecosystems has fundamentally altered this hierarchy. We are seeing a decisive move toward non-metallic prostheses, not merely for their aesthetics, but because digital manufacturing now allows us to harness the unique properties of polymers and ceramics with a precision that was previously unattainable.

In the search for alternatives to traditional titanium and zirconia, PEEK has emerged as a compelling candidate for diverse clinical applications. Its appeal lies primarily in its unique biomechanical profile; with an elastic modulus of approximately, PEEK effectively mimics the flexibility of human bone [10-13]. This 'iso-elastic' behavior provides a critical cushioning effect that attenuates the stress concentrations typically transferred to abutment teeth. Beyond its biomimetic flexibility, the material remains remarkably robust, exhibiting high fatigue and tensile strength alongside the thermal and electrical insulation properties necessary for a stable intraoral environment.

The recent introduction of BioHPP (Bio High-Performance Polymer) represents a significant milestone in the refinement of metal-free restorative options. By reinforcing a PEEK matrix with approximately 20% ceramic fillers, this material transcends the limitations of its unfilled counterparts. This ceramic integration not only augments the structural rigidity and mechanical resilience of the polymer but also optimizes its optical properties. Consequently, BioHPP is increasingly regarded as an indispensable addition to the prosthodontic toolkit, offering a balanced synergy between physiological compatibility and the aesthetic demands of contemporary implantology.

The transformative potential of nanotechnology in prosthodontics is largely predicated on the integration of carbon-based nano-allotropes [5]. Evidence suggests that the incorporation of even a nominal concentration (1%) of carbon particles into an acrylic resin matrix can significantly augment its biomechanical performance. This dopant effect manifests as a dual improvement in flexural and impact strength; interestingly, this enhancement in toughness is accompanied by a concomitant reduction in surface hardness, suggesting a more resilient, less brittle material profile [6 - 7].

Recent developments in prosthodontics have increasingly favored nano-carbon HPPs due to their unique composite architecture. These modern FRCs are specifically engineered to optimize the balance between mechanical resilience and physical mass. In clinical situations where high fracture toughness and resistance to cyclic fatigue are paramount, these fiber-reinforced systems offer a compelling alternative to traditional materials, providing the necessary structural integrity while maintaining a lightweight profile essential for patient comfort and longevity.

When evaluated against glass fiber reinforcements, carbon fibers offer a demonstrably superior biomechanical profile. Their integration into polymeric matrices yields high-stiffness frameworks characterized by exceptional fracture toughness and resistance to both abrasion

and creep. Beyond these mechanical advantages, carbon fibers possess a unique combination of low density and a negligible coefficient of thermal expansion, ensuring dimensional stability. Furthermore, their inherent chemical inertness and biological compatibility make them an ideal candidate for long-term intraoral applications where fatigue resistance is paramount.

The prosthetic frameworks were fabricated using carbon-fiber-reinforced composites, prioritized here for their favorable strength-to-weight ratio and mechanical toughness. Unlike traditional reinforcement phases, carbon fibers offer a unique combination of high fracture resistance and low specific mass, which are critical for minimizing the gravitational load on the supporting abutments. Additionally, the material's inherent fatigue resistance and low thermal conductivity were leveraged to ensure the structural integrity of the complex under simulated masticatory stresses, while its biocompatibility ensured adherence to established clinical safety standards

Therefore, the aim of the present study was to evaluate color stability, surface roughness and Hardness of BioHPP, Nanocarbon HPP and PEEK used for fabrication of prosthetic restoration.

The null hypothesis indicating that there is no statistically significant difference in the color stability, surface roughness, or hardness among BioHPP, PEEK, and nano-carbon reinforced dental materials.

MATERIAL AND METHODS

Sample size was estimated based on assuming confidence level= 95% and study power= 80%. A comparison between the independent means of BioHPP, PEEK and nano-carbon indicated that a sample size of 14 samples per group was required. Total sample size = Number per group x Number of groups = $14 \times 3 = 42$ samples. [8-10]

This study was Experimental study (Randomized controlled trial) in which the Samples were divided randomly (doubl-blind) into three groups according to the materials used for construction of the samples, group I PEEK, group II BioHPP and group III involved nano-carbon reinforced polymers.

1- Samples Fabrication

Cylindrical samples with a diameter of 2 mm and thickness of 5 mm were designed using EXOCAD software and subsequently milled using CAD/CAM technology according to the manufacturer's instructions, finished and finally polished with a low-speed handpiece and diamond polishing paste Renfert polish (Renfert, Hilzingen, Germany), were ultrasonically cleaned for 10 min, and were air-dried.

2- Thermocyclic Aging

The specimens were then subjected to aging by thermal cycling. A total of 10,000 cycles in the water bath (5–55°C, 30 s dwell time and 10 s transfer time) was applied to simulate one year of oral use. The Plates were weighted again on an analytical balance. This protocol was selected based on the standard ISO number 11,405 and simulates the temperature changes that take place in the oral environment.

3- Color Stability

3.A. Staining process

Staining process was carried out by using staining solution which was coffee (Nescafe Classic, Nestle, Vevey, Switzerland) as an acidic medium. The specimens were immersed in staining solution at room temperature for 28-days test period. Solutions were changed daily and put in vials with cover that prevent evaporation of staining solutions. Spectrophotometric analysis was made immediately after light-polymerization (T0) and at 7 (T1), 14 (T2), 21 (T3), 28 (T4) days the beginning of the experimentation.

A digital spectrophotometer (Vita Easysshade Compact, Vita Zahnfabrik, Bad Säckingen, Germany) has been used to determine the precise and reliable shade matching for natural teeth and ceramic restorations. It was also used to evaluate the color stability of the crowns before and after thermocycling and the chewing simulator. The digital spectrophotometer measured the wavelength range from 400 to 700 nm and used LED technology, which was unaffected by the environment.

3.B. Spectrophotometer Analysis

Spectrophotometric analysis was made to determine the precise and reliable shade matching for the specimens, immediately after light-polymerization at the beginning of the study and at 7, 14, 21, 28 days. It was also used to evaluate the color stability of the specimens before and after thermocycling. The digital spectrophotometer (SP820λ; Techkon GmbH, König-Stein, Germany) measured the wavelength range from 400 to 700 nm and used LED technology, which was unaffected by the environment.

Before each measurement, the specimens were gently rinsed with distilled water and air-dried. Color of the specimens was measured with a spectrophotometer against a black background time, late the absence of light in the mouth and against a white background. All specimens were chromatically measured 4 times, and the average values were calculated.

4. Surface Roughness

Surface roughness (SR) measurements were performed using a profilometer (TR200, Beijing TIME High Technology, Beijing, China) on all specimens from each group (n = 14) using the 5 μm diamond stylus with 1.25 mm total length, 0.25 mm cut-off value, 0.02 μm resolution, and a Gaussian filter, according to ISO 4288:1996 [11] before and after each water immersion period and after aging, for each group.

The arithmetic mean value of all peaks and valleys (Ra) in the measured profile was analyzed, and the average value from three measurements in three different directions was

calculated for each specimen. The sampling length was 0.3 mm, and a force of 0.7 mN was applied.

5. Hardness

The Vickers hardness numbers (VHNs) for the tested samples were calculated using a Vickers microhardness tester under 500 Neton of force. A 50 g load was applied by the diamond indenter for a dwell time of 10 s. Five indentation readings were taken for each specimen, and the average of those readings was calculated. Then, for each group, surface hardness was assessed and statistically analyzed both before and after thermocycling to age the materials.

RESULTS

STATISTICAL ANALYSIS

Data were analyzed using IBM SPSS (version 29.0) and R software (version 4.3.2). The achieved results undergo evaluation at a 5% Significance Level, and a 95% Confidence interval.

- ANOVA test was used to identify significance difference among the means of more than two groups, followed by a post hoc test to determine the difference between each pair.
- Nonparametric tests were conducted via Kruskal-Walli's tests to detect significant differences in quantitative variables between different variables.
- Repeated ANOVA test was used to detect the significance of repeated measures of the same group. Graphics were used for data visualization.

Evaluation of Color Stability:

Table (1) This table provides descriptive statistics for each of the three material groups. BioHPP has the highest mean value, followed by nano-carbon Fibers and PEEK.

Evaluation of Surface Roughness:

The tables presented summarize the results of a statistical comparison between three dental materials; group I BioHPP, group II nano-carbon Fibers, and group III PEEK, based on their measured values in an in vitro study.

Table (2) Shows the Tukey HSD post hoc test further confirms this, revealing that all pairwise comparisons between materials are statistically significant ($p < 0.001$). Specifically, PEEK showed significantly higher values than both BioHPP and Carbon Fibers, and BioHPP showed significantly higher values than Carbon Fibers.

Table (3) shows a highly significant difference between the study groups ($p < 0.001$), with a large F-value of 162.356, indicating that the differences in mean values among the materials are statistically significant.

Table (4) shows the descriptive statistics indicate that PEEK has the highest mean value (1.1552), followed by BioHPP (1.0333), and Carbon Fibers (0.6571).

Graph (1) compares the surface roughness of the same three materials. nano-carbon Fibers (orange bars) show the lowest surface roughness across all samples, while BioHPP shows higher roughness, often close to or just below PEEK. PEEK has the highest surface roughness in most samples.

Evaluation of Hardness:

Table (5) shows the results of a Tukey HSD test comparing the means of three materials: BioHPP, nano-carbon Fibers, and PEEK. Significant differences were found between all

material pairs ($p < 0.05$). Carbon Fibers had significantly higher values than both BioHPP and PEEK, while BioHPP also showed higher values than PEEK. The largest mean difference was between Carbon Fibers and BioHPP (3.643), indicating a strong distinction between these two materials. All confidence intervals exclude zero, confirming the statistical significance of the differences.

Table (6) shows the results of a one-way ANOVA used to test whether there are statistically significant differences between the means of three or more independent groups. Nano-carbon Fibers has the highest mean, which likely indicates better performance.

Table (7) This table summarizes the descriptive statistics for each group. Nano-carbon Fibers has the highest mean, and BioHPP the lowest value.

Graph (2) shows a comparison between hardness values of three materials: PEEK, nano-carbon Fibers, and BioHPP in which nano-carbon Fibers consistently have the highest hardness values across all samples while BioHPP has the lowest hardness most of the time. PEEK is often slightly better than BioHPP, but clearly lower than Carbon Fibers.

DISCUSSION

The present in vitro study evaluated the surface roughness, hardness, and color stability of three non-metallic materials, BioHPP, PEEK, and nano-carbon reinforced polymers, used for implant-retained prosthetic applications. Statistically significant differences were observed among all tested materials, leading to rejection of the null hypothesis. These findings confirm that material composition and reinforcement strategy significantly influence the mechanical and surface behavior of polymer-based prosthetic materials used in implant dentistry. [3]

Surface roughness is a clinically relevant factor due to its direct association with plaque accumulation, wear, and long-term prosthesis maintenance. In the current study, nano-carbon

reinforced polymers exhibited the lowest surface roughness values, followed by BioHPP, while PEEK demonstrated the highest roughness. Menini et al. reported similar findings, demonstrating that carbon fiber–reinforced frameworks exhibit improved surface integrity and wear resistance compared with conventional polymer materials used in implant prosthodontics [3]. This finding may be attributed to the reinforcing effect of carbon fibers, which enhance structural homogeneity and resistance to surface degradation.

The higher surface roughness observed in PEEK specimens is consistent with previously published studies evaluating the behavior of PEEK under simulated oral conditions. Porojan et al. demonstrated that thermal cycling and water saturation significantly influence the surface characteristics of dental PEEK, resulting in increased roughness values over time. This behavior has been attributed to the semi-crystalline structure of PEEK and its susceptibility to hydrothermal aging, which may compromise surface smoothness in long-term clinical service. [8]

Regarding hardness, nano-carbon reinforced polymers demonstrated significantly higher hardness values than both BioHPP and PEEK. This result aligns with the findings of Mahmood and Ibrahim, who reported that the incorporation of carbon nanotubes into polymer matrices significantly improves hardness and overall mechanical performance. The reinforcing effect of carbon-based fillers enhances load distribution within the material, increasing resistance to indentation and surface deformation. [6,7]

BioHPP exhibited intermediate hardness and surface roughness values compared with nano-carbon reinforced polymers and PEEK. As a ceramic-filled PEEK-based polymer, BioHPP combines favorable elasticity with improved mechanical performance. Previous studies have highlighted that BioHPP offers biomechanical advantages by reducing stress transmission to implants while maintaining sufficient rigidity for prosthetic frameworks, supporting its clinical application in implant-supported restorations. [12–14]

Color stability is a critical esthetic parameter, particularly for prosthetic materials used in visible zones. In the present study, all tested materials exhibited varying degrees of discoloration following coffee immersion; however, nano-carbon reinforced polymers demonstrated superior color stability compared with PEEK and BioHPP. Similar observations were reported by Porojan et al., who found that PEEK-based materials are susceptible to color changes following aging and exposure to staining media, likely due to increased water sorption and pigment penetration. [8]

From a clinical standpoint, materials exhibiting lower surface roughness, higher hardness, and improved color stability are expected to demonstrate enhanced resistance to wear, reduced plaque accumulation, and improved esthetic longevity. The superior performance of nano-carbon reinforced polymers observed in this study suggests their potential as a reliable metal-free alternative for implant-retained full-arch framework, particularly in patients with high functional demands and esthetic expectations. These findings are in agreement with recent literature emphasizing the growing role of high-performance polymers and fiber-reinforced composites in modern prosthodontics. [9,12]

Additionally, nanocarbon HPP can be used to fabricate the all superstructure of implant-supported prosthesis (framework and teeth). Unlike BioHPP and PEEK, where their use is limited only as framework and must be veneered with another more esthetic material with limitations and problems in bonding and surface treatment.

Despite the favorable outcomes observed, the limitations of this in vitro study must be acknowledged. Laboratory conditions cannot fully replicate the complex oral environment, including cyclic masticatory loads, pH variations, salivary enzymes, and microbial activity. Therefore, although the results are promising, further in vivo investigations and long-term clinical trials are required to validate the clinical performance and longevity of nano-carbon reinforced polymers in implant-supported prosthetic applications. [15]

CONCLUSION

While metallic alloys provide excellent strength and longevity, their aesthetic drawbacks, weight, corrosion potential, and cost have made high-performance polymers and ceramic alternatives increasingly popular for full-arch prosthetics.

Advances in BioHPP, PEEK, and nano-carbon reinforced polymers have offered durable, lightweight, and metal-free solutions that better meet modern patient expectations.

Nanocarbon reinforced polymers demonstrate significant potential as a viable alternative for the fabrication of full arch prostheses. Their exceptional mechanical strength, lightweight nature, and biocompatibility offer distinct advantages over traditional materials. These properties not only enhance the durability and comfort of the prosthesis but also contribute to improved long-term clinical outcomes. As research and development continue, nanocarbon reinforced polymers are poised to play a transformative role in modern prosthodontics.

Recommendations

To ensure the safe and effective application of nano-carbon reinforced polymer (NCRP) in full-arch dental prostheses, both in vivo and in vitro studies are essential. Future research should focus on:

1. In Vitro Studies

- Investigate the mechanical properties (strength, fatigue resistance, and wear) under simulated oral conditions.
- Assess biocompatibility by evaluating potential cytotoxicity and inflammatory responses.
- Study the bonding behavior of NCRP with dental adhesives and cements to optimize retention.

LIMITATION

One of the primary limitations of an in vitro study evaluating new dental materials is the lack of replication of the complex oral environment. In vitro conditions cannot fully mimic factors such as saliva composition, pH fluctuations, masticatory forces, thermal cycling, and microbial activity that occur in the oral cavity.

As a result, the performance of materials observed in a controlled laboratory study may not accurately reflect their behavior in vivo. This gap limits the ability to predict long-term clinical success and may lead to discrepancies when materials are applied in real patient scenarios. Therefore, while in vitro studies are essential for initial assessments, clinical trials are necessary to validate their practical effectiveness and biocompatibility.

List of abbreviations

PEEK: Poly-Ether-Ether-Ketone

BioHPP: Biocompatible high-performance polymer

CAD/CAM: Computer-Aided-Design/Computer-Aided-Manufacturing

Ra: Surface roughness average

VHN: Vickers hardness number

ISO: International Organization for Standardization

Declarations

Ethics approval and consent to participate.

Not applicable

Consent for publication

Not applicable

Availability of data and materials

All datasets and materials used and/or analyzed during the current study are included in this published article.

Competing interests

The authors declare that they have no conflicts of interest.

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Authors' contributions

S.M. M.Z, and R.A conceptualized the study. R.A. collected the required data. R.A conducted the study and interpreted the results. S.M. analyzed the data. R.A wrote the manuscript draft. M.Z and R.A. reviewed and edited the manuscript. The final manuscript was approved by all authors.

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Figures Legends

Fig. 1: A cylindrical sample with a diameter of 2 mm and thickness of 5 mm were designed using EXOCAD software.

Fig. 2: The specimens were then subjected to aging by thermal cycling in which A total of 10,000 cycles in the water bath was applied to simulate one year of oral use.

Fig. 3: The specimens were immersed in staining solution at room temperature for 28-days test period.

Fig. 4: A digital spectrophotometer has been used to determine the precise and reliable shade matching for the specimens.

Fig. 5: The reading of each sample was recorded for future analysis.

Fig. 6: Surface roughness measurements were performed using a profilometer on all specimens from each group using 5 μm diamond stylus.

Fig. 7: The arithmetic mean value of all peaks and valleys in the measured profile was analyzed.

Fig. 8: The Vickers hardness numbers for the tested samples were calculated using a Vickers micro-hardness tester under 500 Newton of force.

Fig. 9: Five indentation readings were taken for each specimen, and the average of those readings was calculated.

Table (1) Descriptive Statistics For Each Of The Three Material Groups

Descriptives

Values

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum	Between-Component Variance
					Lower Bound	Upper Bound			
BioHPP	13	5.25308	2.592201	.718947	3.68663	6.81953	1.640	8.960	
Carbon Fibers	13	4.78615	2.118555	.587581	3.50592	6.06638	1.640	8.960	
PEEK	13	4.27385	1.865746	.517465	3.14639	5.40131	1.640	8.960	
Total	39	4.77103	2.191507	.350922	4.06062	5.48143	1.640	8.960	
Model	Fixed Effects		2.212750	.354324	4.05242	5.48963			
	Random Effects			.354324 ^a	3.24649 ^a	6.29556 ^a			-.136741

a. Warning: Between-component variance is negative. It was replaced by 0.0 in computing this random effects measure.

Table (2) Shows the Tukey HSD post hoc test for evaluation of surface roughness

Multiple Comparisons

Dependent Variable: Values

	(I) Materialcode	(J) Materialcode	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	BioHPP	Carbon Fibers	.3761429 [*]	.0288154	<.001	.305940	.446346
		PEEK	-.1219286 [*]	.0288154	<.001	-.192132	-.051725
	Carbon Fibers	BioHPP	-.3761429 [*]	.0288154	<.001	-.446346	-.305940
		PEEK	-.4980714 [*]	.0288154	<.001	-.568275	-.427868
	PEEK	BioHPP	.1219286 [*]	.0288154	<.001	.051725	.192132
		Carbon Fibers	.4980714 [*]	.0288154	<.001	.427868	.568275

*. The mean difference is significant at the 0.05 level.

Table (3) show a highly significant difference between the study groups ($p < 0.001$), with a large F-value of 162.356, indicating that the differences in mean values among the materials are statistically significant.

ANOVA

Values

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.887	2	.944	162.356	<.001
Within Groups	.227	39	.006		
Total	2.114	41			

Table (4) shows the descriptive statistics indicate that PEEK has the highest mean value (1.1552), followed by BioHPP (1.0333), and Carbon Fibers (0.6571).

Descriptives									
Values									
	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum	Between-Component Variance
					Lower Bound	Upper Bound			
BioHPP	14	1.033286	.0663017	.0177199	.995004	1.071567	.9390	1.1600	
Carbon Fibers	14	.657143	.0223326	.0059687	.644248	.670037	.6240	.6930	
PEEK	14	1.155214	.1119919	.0299311	1.090552	1.219876	.9360	1.3020	
Total	42	.948548	.2270702	.0350377	.877788	1.019308	.6240	1.3020	
Model	Fixed Effects		.0762383	.0117638	.924753	.972342			
	Random Effects			.1498935	.303608	1.593487			.0669890

Graph (1) compares the surface roughness of the same three materials. nano-carbon Fibers (orange bars) show the lowest surface roughness across all samples, while BioHPP shows higher roughness, often close to or just below PEEK. PEEK has the highest surface roughness in most samples.

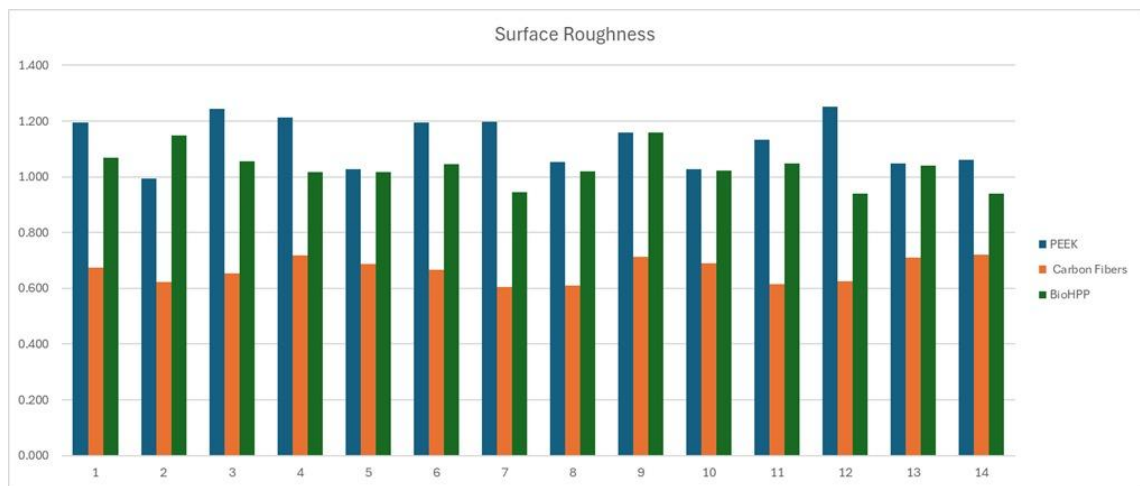


Table (5) shows the results of a Tukey HSD test comparing the means of three materials: BioHPP, nano-carbon Fibers, and PEEK.

Multiple Comparisons

Dependent Variable: Values

	(I) Materialcode	(J) Materialcode	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
Tukey HSD	BioHPP	Carbon Fibers	-3.643 [*]	.422	<.001	-4.67	-2.61
		PEEK	-1.286 [*]	.422	.011	-2.31	-.26
	Carbon Fibers	BioHPP	3.643 [*]	.422	<.001	2.61	4.67
		PEEK	2.357 [*]	.422	<.001	1.33	3.39
	PEEK	BioHPP	1.286 [*]	.422	.011	.26	2.31
		Carbon Fibers	-2.357 [*]	.422	<.001	-3.39	-1.33

*. The mean difference is significant at the 0.05 level.

Table (6) shows the results of a one-way ANOVA used to test whether there are statistically significant differences between the means of three or more independent groups.

ANOVA

Values

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	95.571	2	47.786	38.257	<.001
Within Groups	48.714	39	1.249		
Total	144.286	41			

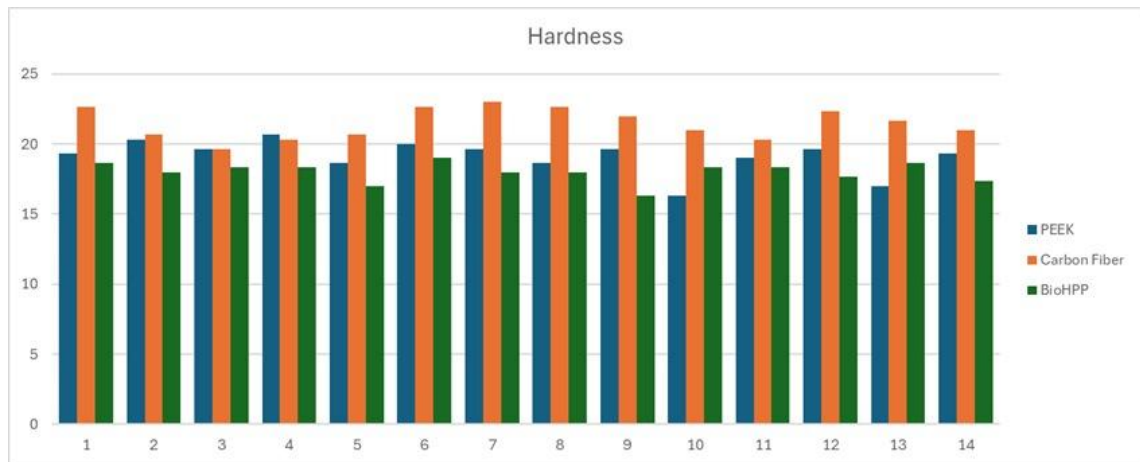
Table (7) This table summarizes the descriptive statistics for each group. Nano-carbon Fibers has the highest mean, and BioHPP the lowest value.

Descriptives

Values

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum	Between-Component Variance
BioHPP	14	17.93	.829	.221	17.45	18.41	16	19	
Carbon Fibers	14	21.57	1.158	.309	20.90	22.24	20	23	
PEEK	14	19.21	1.311	.350	18.46	19.97	16	21	
Total	42	19.57	1.876	.289	18.99	20.16	16	23	
Model									
Fixed Effects				1.118	.172	19.22	19.92		
Random Effects				1.067		14.98	24.16		3.324

Graph (2) shows a comparison between hardness values of three materials: PEEK, nano-carbon Fibers, and BioHP.



Figures

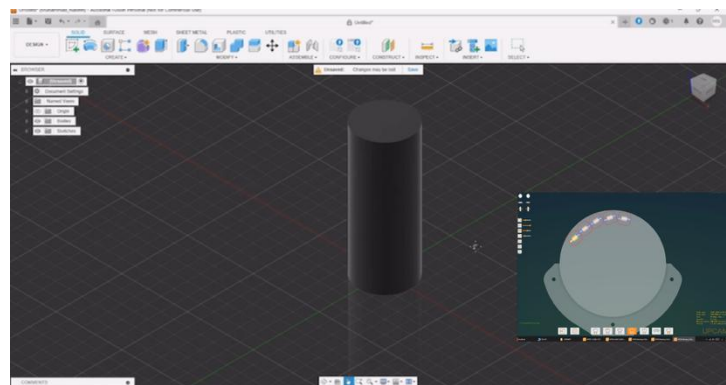


Fig. 1: A cylindrical sample with a diameter of 2 mm and thickness of 5 mm were designed using EXOCAD software.



Fig. 2: The specimens were then subjected to aging by thermal cycling in which A total of 10,000 cycles in the water bath was applied to simulate one year of oral use.



Fig. 3: The specimens were immersed in staining solution at room temperature for 28-days test period.



Fig. 4: A digital spectrophotometer has been used to determine the precise and reliable shade matching for the specimens.



Fig. 5: The reading of each sample was recorded for future analysis.



Fig. 6: Surface roughness measurements were performed using a profilometer on all specimens from each group using 5 μm diamond stylus.

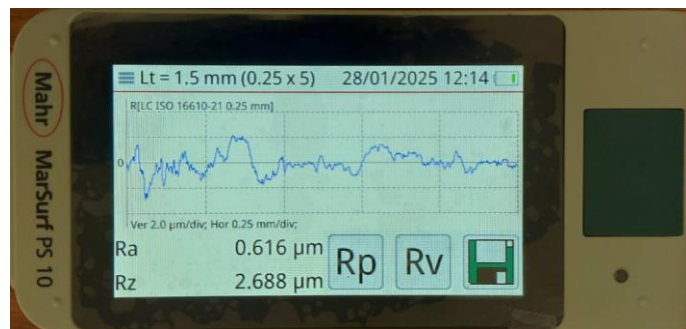


Fig. 7: The arithmetic mean value of all peaks and valleys in the measured profile was analyzed.



Fig. 8: The Vickers hardness numbers for the tested samples were calculated using a Vickers micro-hardness tester under 500 Newton of force.

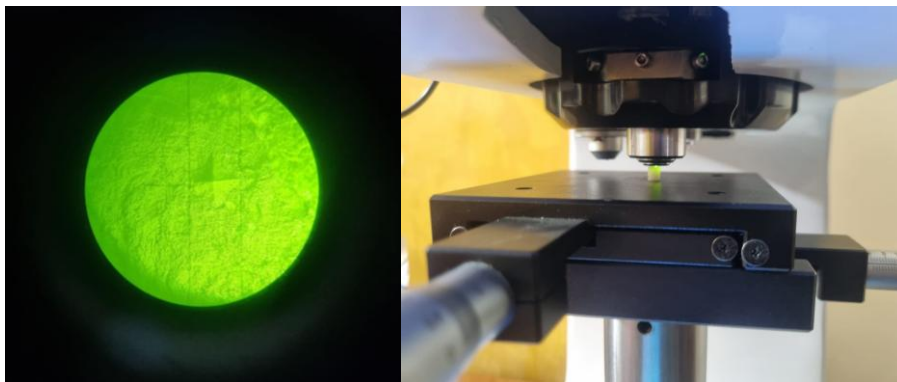


Fig. 9: Five indentation readings were taken for each specimen, and the average of those readings was calculated.