Review

Dicle Dent J. 2025;26(1):5-10

Improving PMMA in prosthodontics: a literature review

Nuran Yanıkoğlu, Osayd Alawawda
Department of Prosthodontics, Faculty of Dentistry, Atatürk University, Erzurum, Turkiye

Cite this article as: Yanıkoğlu N, Alawawda O. Improving PMMA in prosthodontics: a literature review. *Dicle Dent J.* 2025;26(1):5-10.

Received: 07.12.2024 ◆ **Accepted**: 14.03.2025 ◆ **Published**: 28.03.2025

ABSTRACT

Since its introduction in the 1930s, PMMA has been the primary denture base material in use. This is due to the fact that PMMA is affordable, visually pleasing, and medically compatible. Nonetheless, PMMA's intrinsic flaws-primarily its poor flexural strength and impact resistance-make it imperative to look for solutions to address these two crucial deficiencies. The latest developments involve the insertion of silver, zirconium oxide (ZrO_2), and titanium dioxide (TiO_2) nanoparticles, which are said to increase the mechanical characteristics even further, such as flexural strength, hardness, and wear resistance. To further increase the impact strength and durability of PMMA, fibers can be added to the material. These fibers can be synthetic (like polyester or carbon) or natural (like sisal or bamboo). Improvements in surface treatments and bonding methods have also strengthened PMMA's binding and made it more compatible with other materials. Aging research demonstrates that reinforced PMMA is more resilient to environmental stress, making it a material of choice for long-term dental applications. Furthermore, the use of antimicrobial compounds and nanoparticles offers additional benefits, such as the presence of antifungal qualities that mitigate biofilm development and improve the overall biocompatibility of dental prostheses. These developments thus suggest that there is still a lot of promise for the modified PMMA in dental applications, both in terms of improving performance and extending its useful life in a clinical setting. The aim of this review is to explore the advancements in reinforcing PMMA (polymethyl methacrylate) for dental prosthetics by analyzing various modifications.

Keywords: Polymethyl methacrylate, PMMA, nanoparticle reinforcement, fiber reinforcement, denture base materials, mechanical properties

INTRODUCTION

Polymethyl methacrylate (PMMA) has long been established as the primary material for denture bases due to its advantageous properties, such as ease of manipulation, aesthetic appeal, biocompatibility, and cost-effectiveness. Since its introduction in the 1930s, PMMA has revolutionized prosthodontics, offering a practical solution for denture fabrication and other dental applications. Its ability to be easily molded, colored, and processed at relatively low temperatures makes it an ideal choice for dental laboratories and clinicians like. Despite these benefits, PMMA has inherent limitations, particularly in its mechanical properties. One of the significant drawbacks is its low flexural strength, which can lead to fractures under the repetitive stress and strain encountered in the oral environment. Impact resistance is another concern, as PMMA can be prone to cracking or breaking if subjected to sudden forces, such as accidental drops or heavy occlusal loads.[1]

For instance, the inclusion of nanoparticles like titanium dioxide (TiO_2)[2] and zirconium oxide (ZrO_2)[3] has been shown to improve the flexural strength and hardness of PMMA, thereby increasing its resistance to wear and fracture.

Fiber reinforcement is another approach that has gained popularity. By integrating different types of fiber into PMMA, the impact resistance and fracture toughness can be significantly improved.[4] These reinforcements help distribute the applied stress more evenly throughout the material, reducing the likelihood of failure under load[4] Additionally, the incorporation of antimicrobial agents, such as, into the PMMA has been explored to further enhance the material's resistance to microbial colonization. Nanoparticles such as TiO_2[5] nanosilver (AGNP)[6] ZnO and nano silicon dioxide (SiO_2)[7] can also confer additional benefits, such as antimicrobial properties, which are particularly valuable in reducing biofilm formation on denture surfaces. The aim of this review is to explore the advancements in reinforcing PMMA for dental prosthetics by analyzing various modifications.

NANOPARTICLE REINFORCEMENT IN ACRYLIC RESINS

The growth and nanotechnology and scope of its application has revolutionized the dental field progressing to the emergence of "nano dentistry".[8] The incorporation of nanoparticles into acrylic resins has garnered significant recent research interest, particularly concerning their influence on the mechanical and thermal properties of denture-based materials.[9] For instance, the addition of nanoparticles such as silver (Ag) has been shown to enhance hardness and wear resistance.[10] Other

Corresponding Author: Osayd Alawawda, osayd33540@gmail.com

nanoparticles, such as aluminum oxide [11]and cerium oxide,[12] have been identified to improve thermal conductivity and mitigate mechanical degradation, respectively. These findings highlight the inherently trade-off nature of reinforcement in dental materials.

In a recent study, Elhmali et al.[13] examined the mechanical performance of PMMA modified with poly (4-styrenesulfonic acid-co-maleic anhydride) sodium salt and strontium titanate, showing effective enhancement in terms of strength and durability. Similarly, other studies have examined acrylic resins modified with metal and ceramic nanoparticles, reporting enhanced hardness and physical properties. [14]Another investigation focused on the tribological, microhardness, and color stability properties of heat-cured acrylic resin denture bases reinforced with various nanofillers, highlighting the multifunctional benefits achieved through nanoparticle incorporation.[15]

Barapatre et al.[16] studied the reinforcement of PMMA resin with nanoparticles of polyetheretherketone, zirconium oxide, and their mixture for the improvement of flexural strength, which could prove to have improved mechanical properties. Karci et al.[17] evaluated the flexural strength of various denture base materials reinforced with different nanoparticles, showing that these reinforcements significantly enhance the material's performance. Alzayyat et al.[18] investigated the effects of silicon dioxide (SiO_2) nanoparticles on the flexural properties of denture base resins, demonstrating that such reinforcement significantly enhances durability and mechanical properties. Their findings included the use of SiO_2 nanoparticles to improve the flexural strength of repaired acrylic denture base materials, showcasing the potential of nanoparticles to extend the life span of dental prosthetics. [19] Nanoparticles are also instrumental in reducing polymerization shrinkage, a common challenge in dental resins, by modifying the resin matrix. Methacrylate- and epoxy-functionalized nanocomposites have been developed to enhance the stability and longevity of dental restorations.[20] Additionally, nanoparticles improve the heat resistance of dental resins, mitigating the risk of thermal degradation and ensuring long-term material performance.[21] Due to their nanoscale size, these particles enable precise control over the optical properties of dental materials, leading to superior aesthetic outcomes as resins can closely replicate the natural appearance of teeth.[22] The use of biocompatible nanoparticles, such as titanium dioxide and iron oxide, ensures that modified resins are safe for use in the oral cavity. These nanoparticles also reduce microbial adhesion, further improving the clinical performance of dental resins.[23] Despite their numerous benefits, challenges such as nanoparticle agglomeration and chemical instability must be addressed to fully realize their potential in clinical applications. Ongoing research is focused on overcoming these obstacles to develop more effective and reliable dental materials.[24]

FIBER REINFORCEMENT IN ACRYLIC RESINS

One critical area of study aimed at improving the mechanical properties and expanding the applications of polymer composites, particularly acrylic resins, is the integration of various types of fibers. Among the options explored, natural fibers, such as those derived from bamboo and pineapple leaves, have shown considerable promise as environmentally friendly solutions for reinforcement. Research suggests that these fibers enhance the mechanical properties of composite materials while supporting the development of sustainable alternatives.[25,26]

In contrast, synthetic fibers, such as polyester and polypropylene, have been extensively investigated for their ability to enhance the physical characteristics and durability of composite materials. Studies indicate that combining natural and synthetic fibers can yield notable improvements in material performance, making synthetic fibers a valuable component in composite reinforcement.[27] Additionally, high-performance fibers, such as aramid and carbon fibers, are recognized for their superior mechanical properties, including increased stiffness, durability, and resistance to corrosion. The work of Alam et al.[28] underscores the relevance of these high-performance fibers in advanced engineering applications requiring exceptional material performance. This ongoing research offers a more comprehensive understanding of the roles played by high-performance, natural, and synthetic fibers in enhancing the mechanical properties and real-world applications of polymer composites.

In a study examining the impact strength of fiber-reinforced acrylic resin following sisal fiber alkalization, Benyamin et al.[29] demonstrated the effectiveness of natural fibers in enhancing the toughness of denture bases. Similarly, Sharhan et al.[30] explored the benefits of synthetic fiber reinforcement, specifically polypropylene and polyacrylonitrile fibers, in improving surface roughness, hardness, and compression resistance for denture applications. Gonçalves et al.[31] investigated the impact of polymeric nanofibers on the mechanical properties of PMMA resin, demonstrating the potential of both natural and synthetic fibers to enhance material performance. Further advancements in the field were highlighted by Ardakani et al.[32] who examined the flexural strength of PMMA reinforced with metal mesh and high-performance polymers, reporting significant improvements for stress-bearing applications. Nayak et al.[33] compared various fiber reinforcement patterns and their effects on the mechanical properties of heat-polymerized acrylic resin. Their findings revealed that fiber reinforcement in meshwork patterns significantly enhances the flexural strength of PMMA compared to transverse reinforcement patterns. Moreover, PMMA reinforced with basalt fibers (BF) exhibited superior flexural strength compared to those reinforced with glass fibers (GF).

High-performance fibers, such as poly (p-phenylene-2,6-benzobisoxazole) (PBO), have been shown to significantly enhance the mechanical properties of dental fiber-reinforced composites (FRCs), broadening their utility in various applications. The integration of nanomaterials, such as ZnO nanoparticles and nanowires, into PBO fibers has improved interfacial adhesion with the resin matrix, resulting in notable increases in interfacial shear strength and flexural properties. For instance, the innovative PBO-ZnO nanowire and polyhedral oligomeric silsesquioxane (POSS) hierarchical reinforcement configuration achieved an exceptional flexural strength of 925.0±39.2 MPa and a flexural modulus of 39.39±1.41 GPa. These properties are comparable to those of human dentin, highlighting its potential for dental applications.[34] Synthetic fibers, particularly glass and carbon fibers, have seen widespread use in dental applications due to their advantageous mechanical properties. Glass fibers, in particular, are favored for their superior aesthetic qualities and their ability to form strong bonds with resins when treated with silane coupling agents. This treatment enhances adhesion in composite materials and facilitates effective load transfer from the weaker polymer matrix to the more robust reinforcing fibers, substantially improving the overall strength and longevity of composite materials used in dental restorative practices.[35] Despite their advantages, fiber-reinforced composites face challenges such as fractures, wear from mastication, and delamination. While these issues can often be resolved cost-effectively, they underscore the need for careful material selection and design in dental applications. Additionally, the mechanical properties of fiber-reinforced composites may deteriorate after hydrolytic aging, which is a significant consideration for ensuring their long-term durability.[36]

SURFACE TREATMENTS AND BONDING TECHNIQUES

The intrinsic qualities of PMMA (polymethyl methacrylate) often present challenges in direct bonding and material compatibility, necessitating tailored surface treatments to enhance bond strength and compatibility.[37] Klaiber et al.[37] investigated the bonding behavior of industrial CAD/CAM PMMA, artificial resin teeth and traditional PMMA, concluding that monomer application was the most effective surface treatment. Similarly, Gad et al.[38] explored the incorporation of zirconium oxide nanoparticles and surface treatments to improve the flexural strength of PMMA denture base materials, showcasing advancements in nanotechnology for PMMA enhancement.

Further studies have explored plasma and laser treatments for PMMA surface modification, underlining the importance of ongoing research in this area.[39]

Schauperl et al.[40] examined the effects of various surface treatments on acrylic denture base materials reinforced with woven glass fibers, demonstrating improved bonding and overall mechanical properties. Taczała-Warga et al.[41] highlighted the significance of pre-treating acrylic surfaces in denture restorations, particularly for cellulose fiber-reinforced denture base acrylic. Deb et al.[42] assessed how different acrylic resin repair methods influence the flexural strength of denture bases, providing practical guidelines for successful repairs. Alumina abrasive blasting (AB) has emerged as a proficient technique for improving surface roughness and adhesive strength. Integrated treatments combining AB with chemical agents like methylene chloride (CH) significantly enhanced flexural, shear, and impact strengths, though careful regulation of exposure duration is crucial to prevent adverse effects.[43] Adhesive primers also significantly enhance PMMA bond strength, particularly with silicon soft denture liners (SDL) under thermocycling conditions, which simulate thermal stress in oral environments.[44] Production methods impact PMMA-based material performance, with conventional and subtractive techniques yielding higher shear bond strength than additive methods. Airborne-particle abrasion with 50 µm particles effectively maintains adhesion in such contexts.[45]

In digital workflows, surface treatments play a critical role in integrating custom artificial resin teeth into milled PMMA bases. Monomer application remains the most effective treatment, while treatments like nitrogen plasma may impair bond strength.[46] Despite these advancements, challenges such as material compatibility and treatment specificity persist. Research into hybrid materials and alternative thermoplastics may offer novel solutions, paving the way for superior dental prosthetic materials. [47]

AGING AND DURABILITY OF REINFORCED ACRYLIC RESINS

Environmental stress significantly affects the performance and longevity of reinforced acrylic resins, emphasizing the need for materials with enhanced durability. Studies comparing sandwich constructions with polystyrene cores and cellulose foam under UV and rain exposure have illustrated variable degradation effects.[48] Davies et al.[49] found that seawater impacts acrylic matrix composites differently, with certain reinforced resins demonstrating superior resistance to water-aging processes.

Al-Jumal et al.[50] examined the hardness of heat-cured denture base resin modified with recycled acrylic resin during artificial aging, underscoring the importance of long-term material durability. Rahaman Ali et al.[51] evaluated the impact of heat cycles on the flexural properties of denture base acrylic resins reinforced with microcrystalline cellulose (MCC), identifying MCC as a viable substitute for synthetic reinforced PMMA resins. Çakmak et al.[52] investigated heat cycling's effects on flexural strength and hardness in new-generation denture base materials, finding that thermal cycling reduced flexural strength across all resins. Notably, thermal cycling decreased the microhardness of milled PMMA but did not affect 3D-printed resin. Apimanchindakul et al.[53] highlighted the potential of 1% short E-glass fiber reinforcement in self-cured acrylic resin to increase flexural strength. Environmental factors such as temperature and humidity profoundly influence the mechanical properties of acrylic resins. High temperatures can cause thermal oxidative degradation, weakening the material's mechanical strength over time.[54] Humidity affects dimensional stability, potentially causing cracks due to volume changes.[55] UV exposure accelerates polymer degradation, leading to embrittlement and reduced mechanical performance, primarily due to polymer chain scissions compromising material integrity.[56]

ANTIFUNGAL AND ANTIMICROBIAL PROPERTIES

PMMA faces challenges in terms of mechanical strength and surface characteristics, leading to potential issues with fungal adhesion and biofilm development, both of which contribute to denture stomatitis.[18] Researchers have explored various strategies to enhance the material's resistance to these issues. Jang et al.[57] assessed the antifungal and physicochemical properties of a polymerized acrylic resin modified with strontium-based phosphate glass. Their findings suggested that incorporating nanoparticles could improve antibacterial activity. Al-Eraky et al.[58] investigated the antifungal and antibiofilm effects of caffeine against *Candida albicans* on PMMA denture base material, offering a novel approach to enhancing the safety and biocompatibility of dental prostheses. In a similar vein, Alzayyat et al.[59] explored the antifungal efficacy of PMMA denture base material enhanced with SiO2 nanoparticles, providing an effective solution for combating infections commonly associated with dentures. Further investigations by Gad et al. [3]incorporated ZrO2 nanoparticles and glass fibers into PMMA, leading to enhanced mechanical strength and antifungal properties. Silver nanoparticles (AgNPs) are widely recognized for their potent antimicrobial effects, and when added to PMMA, they exhibit significant antibacterial and antifungal activity against pathogens like Streptococcus mutans, Lactobacillus, and *Candida albicans*. The inclusion of AgNPs in PMMA not only enhances antimicrobial properties but also improves the material's mechanical strength, making it more suitable for dental applications.[60] Zinc oxide (ZnO) nanoparticles have similarly demonstrated antimicrobial effects, particularly when combined with silver ions, boosting overall antimicrobial activity against oral pathogens.[60] Bioactive glass and calcium phosphate compounds are integrated into PMMA to improve its bioactive and antimicrobial properties. Although bioactive glass enhances mineral induction capacity, its direct antimicrobial effects may be somewhat limited.[7] Chitosan nanoparticles and organic coatings such as ammonium chitosan and sodium alginate further improve the antimicrobial properties of PMMA by acting as barriers to microbial adhesion and facilitating the targeted delivery of antimicrobial agents.[7] However, while nanoparticles enhance antimicrobial properties, careful evaluation of their cytotoxicity is crucial. Studies have shown that PMMA composites containing nanoparticles like silver and peppermint oil are biocompatible, but the concentration and distribution of these nanoparticles need to be optimized to prevent adverse effects.[61]

SELF-HEALING PMMA

Self-healing PMMA is a promising area of research, utilizing nanocapsules that contain healing agents. These capsules release their contents upon damage, initiating a repair process. For example, a dual nanocapsule system containing an initiator and a monomer has shown the ability to enable self-healing in dental resins. In one study, 33% of samples demonstrated the capacity to be reloaded and tested in tension after healing.[62] The self-healing property is particularly valuable in extending the lifespan of dental prostheses, as it enables the material to repair micro-cracks that often lead to failure in dental applications.[63] Recent developments in photo-initiator systems and the use of biocompatible materials have significantly improved the biocompatibility of self-healing systems, reducing the risk of adverse reactions in dental polymers.[64]

Self-healing systems, which rely on the incorporation of microcapsules within the PMMA matrix, have shown promising results. When fractures occur, the capsules release healing agents that restore the material's integrity, effectively repairing damage to the material and prolonging the life of dental prostheses.[65] According to Harb et al.[66] self-healing PMMA- cerium oxide coatings with outstanding anticorrosive performance and endurance have prospective applications. Cerium ions act as self-healing agents by preventing the corrosion front from advancing. Although the development of self-healing PMMA for dental applications is highly promising, challenges remain in optimizing the efficiency of healing processes and ensuring the biocompatibility of the materials used.

CONCLUSION

Because of its many advantageous qualities, PMMA has long been used as a foundational material in prosthodontics, particularly in the field of denture bases. But its shortcomings in terms of durability and mechanical strength have sparked a lot of study into improving its overall performance. Fiber reinforcement with nanofillers the flexural strength, impact strength, and general toughness of PMMA were greatly increased by the addition of nanoparticles and fiber reinforcement, which made it more resilient to the demanding circumstances found in the oral environment. Its compatibility was further increased by bonding procedures and surface treatments, and then antimicrobial agents were added to make it more resistant to microbial colonization and more biocompatible. These advancements in the field have not only increased the longevity of PMMA-based materials but, interestingly, have also expanded its clinical applicability, demonstrating the material's continued importance and value in contemporary dentistry. PMMA-based materials will become even more resilient and adaptable via more research and development in this area, confirming its significance for use in dental prostheses and other applications.

ETHICAL DECLARATIONS

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

The authors declared that this study has received no financial support.

Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

REFERENCES

1. Apimanchindakul C, Na Nan P, Aimjirakul N. Effect of reinforced self-cured acrylic resin on flexural strength. *Int J Dent*. 2022;2022:2698995. doi:10.1155/2022/2698995
2. Altarazi A, Haider J, Alhotan A, Silikas N, Devlin H. 3D printed denture base material: the effect of incorporating TiO_2 nanoparticles and artificial ageing on the physical and mechanical properties. *Dent Mater*. 2023;39(12):1122-1136. doi:10.1016/j.dental.2023.10.005
3. Gad MM, Rahoma A, Abualsaud R, et al. Influence of artificial aging and ZrO2 nanoparticle-reinforced repair resin on the denture repair strength. *J Clin Exp Dent*. 2020;12(4):e354-e362. doi:10.4317/jced.56610
4. Sharhan HA, N.rasheed Z, Oleiwi JK. Effect of polypropylene (PP) and polyacrylonitrile (PAN) fibers reinforced acrylic resin on compression, hardness and surface-roughness for denture applications. *Key Engineer Mater*. 2022;911:9-16. doi:10.4028/p-197rys
5. Anehosur GV, Kulkarni RD, Naik MG, Nadiger RK. Synthesis and determination of antimicrobial activity of visible light activated TiO_2 nanoparticles with polymethyl methacrylate denture base resin against *Staphylococcus aureus*. *J Gerontol Geriat Res*. 2012;1(1):103-111.doi:10.4172/jggr.1000103
6. Sun J, Wang L, Wang J, et al. Characterization and evaluation of a novel silver nanoparticles-loaded polymethyl methacrylate denture base: in vitro and in vivo animal study. *Dent Mater J*. 2021;40(5):1100-1108. doi:10.4012/dmj.2020-129
7. Sati S, Bamola VD, Chaudhry R, Jit BP, Gupta M. Nanoparticles and inert coating materials: a potential enhancer of antimicrobial property of polymethyl-methacrylate (PMMA) based denture. *J Dent Oral Epidemiol*. 2023;3(2):1-12. doi:JDOE2200107
8. Choubisa D. An overview of applications of nanotechnology in prosthodontics. *J Prosthodont Dent*. 2022;17,1-22.
9. Köroğlu A, Şahin O, Kürkçüoğlu I, Dede DÖ, Özdemir T, Hazer B. Silver nanoparticle incorporation effect on mechanical and thermal properties of denture base acrylic resins. *J Appl Oral Sci*. 2016;24(6):590-596. doi:10.1590/1678-775720160185
10. Altaie SF. Tribological, microhardness and color stability properties of a heat-cured acrylic resin denture base after reinforcement with different types of nanofiller particles. *Dent Med Probl*. 2023;60(2):295-302. doi:10.17219/dmp/137611
11. Barzegar A, Ghaffari T, Parizad A. Effect of incorporating aluminum oxide nanoparticles on thermal conduction and flexural strength of acrylic resins. *Dent Res J (Isfahan)*. 2022;19:33.
12. Machado-Santos L, Silikas N, Baroudi K, Sinhoreti MA, Brandt WC, Liporoni PC. Mechanical performance of experimental acrylic resins modified by nanoparticles after chemical and mechanical degradation. *J Clin Exp Dent*. 2020;12(12):e1157-e1163. doi:10.4317/jced.57265
13. Elhmali HT, Stajcic I, Petrovic M, et al. Mechanical performance of denture acrylic resin modified with poly (4-styrenesulfonic acid-*co*-maleic anhydride) sodium salt and strontium titanate. *Polym Compos*. 2024;45(12):11404-11415. doi:10.1002/pc.28574
14. Machado-Santos L, Baroudi K, Silikas N, et al. Physical analysis of an acrylic resin modified by metal and ceramic nanoparticles. *Dent Med Probl*. 2023;60(4):657-664. doi:10.17219/dmp/171844
15. Altaie SF. Tribological, microhardness and color stability properties of a heat-cured acrylic resin denture base after reinforcement with different types of nanofiller particles. *Dent Med Probl*. 2023;60(2):295-302. doi:10.17219/dmp/137611
16. Barapatre D, Somkuwar S, Mishra SK, Chowdhary R. The effects of reinforcement with nanoparticles of polyetheretherketone, zirconium oxide and its mixture on flexural strength of PMMA resin. *Eur Oral Res*. 2022;56(2):61-66. doi:10.26650/eor.2022904564
17. Karci M, Demir N, Yazman S. Evaluation of flexural strength of different denture base materials reinforced with different nanoparticles. *J Prosthodont*. 2019;28(5):572-579. doi:10.1111/jopr.12974
18. Alzayyat ST, Almutiri GA, Aljandan JK, et al. Antifungal efficacy and physical properties of poly(methylmethacrylate) denture base material reinforced with SiO2 nanoparticles. *J Prosthodont*. 2021;30(6):500-508. doi:10.1111/jopr.13271
19. Gad MMA, Abualsaud R, Al-Thobity AM, et al. Effect of SiO2 nanoparticles addition on the flexural strength of repaired acrylic denture base. *Eur J Dent*. 2020;14(1):19-23. doi:10.1055/s-0039-1701076
20. Chen MH. Update on dental nanocomposites. *J Dent Res*. 2010;89(6):549-560. doi:10.1177/0022034510363765
21. Kuşçu HYY. Utilization of nanomaterials in prosthetic dental treatment. *HRU Int J Dent Oral Res*. 2023;3(2):117-123. doi:10.61139/ijdor.1270852
22. Santulli C. Nanostructured polymer composites for dental fillings. Nanostructured polymer composites for biomedical applications. Elsevier, 2019:277-293.
23. Acosta-Torres LS, Lpez-Marín LM, Núñez-Anita RE, Hernández-Padrón G, Castaño VM. Biocompatible metal-oxide nanoparticles: nanotechnology improvement of conventional prosthetic acrylic resins. *J Nanomater*. 2011;2011(1):941561. doi:10.1155/2011/941561
24. Bastos NA, Bitencourt SB, Martins EA, De Souza GM. Review of nano-technology applications in resin-based restorative materials. *J Esthet Restor Dent*. 2021;33(4):567-582. doi:10.1111/jerd.12699
25. Surajarusarn B, Thaiwattananon S, Thanawan S, Mougin K, Amornsakchai T. Realising the potential of pineapple leaf fiber as green and high-performance reinforcement for natural rubber composite with liquid functionalized rubber. *Fibers Polymers*. 2021;22(9):2543-2551.
26. Bittner CM, Oettel V. Fiber reinforced concrete with natural plant fibers investigations on the application of bamboo fibers in ultra-high performance concrete. *Sustainability*. 2022;14(19):12011. doi:10.3390/su141912011
27. Andrzejewski J, Szostak M. Preparation and characterization of the injection molded polymer composites based on natural/synthetic fiber reinforcement. *Lecture Notes Mechanic Engineer*. 2019:473-484.
28. Alam MI, Maraz KM, Khan RA, Alam MI, Maraz KM, Khan RA. A review on the application of high-performance fiber-reinforced polymer composite materials. *GSC Advanced Res Rev*. 2022;10(2):20-36. doi:10.30574/gscarr.2022.10.2.0036
29. Benyamin B, Amurwaningsih M, Darwis WY. The sisal fiber (agave sisalana) alkalization effects on the impact strength of fiber reinforced acrylic resin. *J Medali*. 2022;4(3):25-33. doi:10.30659/medali.4.3.25-33
30. Sharhan HA, Alraziqi ZNR, Oleiwi JK. Effect of polypropylene (PP) and polyacrylonitrile (PAN) fibers reinforced acrylic resin on compression, hardness and surface-roughness for denture applications. *Key Engineer Mater*. 2022;911:9-16. doi:10.4028/p-197rys
31. Gonçalves NI, Münchow EA, Santos JD, et al. The role of polymeric nanofibers on the mechanical behavior of polymethyl methacrylate resin. *J Mech Behav Biomed Mater*. 2020;112:104072. doi:10.1016/j.jmbbm.2020.104072
32. Ardakani ZH, Giti R, Dabiri S, Hosseini AH, Moayedi M. Flexural strength of polymethyl methacrylate reinforced with high-performance polymer and metal mesh. *Dent Res J (Isfahan)*. 2021;18:30.
33. Nayak K, Rahangdale TD, Shrivastava S, Newaskar PS, Mishra N, Noorani SM. Evaluation and comparison of mechanical properties of heat polymerized acrylic resin after reinforcement of different fibers in different patterns: an in vitro study. *Cureus*. 2023;15(5):e39564. doi:10.7759/cureus.39564
34. Hu C, Lin YQ, Yang YJ, et al. High-performance dental composites based on hierarchical reinforcements. *J Dent Res*. 2022;101(8):912-920. doi:10.1177/00220345221074909
35. Vallittu PK. Fibre-reinforced composites (FRCs) as dental materials. *Non Metall Biomater Tooth Repair Replacem*. 2013:352-374.
36. Kumar A, Tekriwal S, Rajkumar B, Gupta V, Rastogi R. A review on fibre reinforced composite resins. *Ann Prosthodont Restorat Dent*. 2016;2(4):11-16.
37. Klaiber D, Spintzyk S, Geis-Gerstorfer J, Klink A, Unkovskiy A, Huettig F. Bonding behavior of conventional PMMA towards industrial CAD/CAM PMMA and artificial resin teeth for complete denture manufacturing in a digital workflow. *Materials (Basel)*. 2021;14(14):3822. doi:10.3390/ma14143822
38. Gad MM, Rahoma A, Abualsaud R, et al. Impact of different surface treatments and repair material reinforcement on the flexural strength of repaired PMMA denture base material. *Dent Mater J*. 2020;39(3):471-482. doi:10.4012/dmj.2018-436
39. Calderon Salazar P, Huybrechts L. PD otherwise will be pluriversal (or it won't be). *ACM Int Confer Proceed Series*. 2020;1:107-115. doi:10.1145/3385010.3385027
40. Schauperl Z, Ivanković L, Bauer L, Šolić S, Ivanković M. Effects of different surface treatments of woven glass fibers on mechanical properties of an acrylic denture base material. *Int J Mol Sci*. 2023;24(2):909. doi:10.3390/ijms24020909
41. Taczała-Warga J, Sawicki J, Krasowski M, Sokołowski J. The effect of acrylic surface preparation on bonding denture teeth to cellulose fiber-reinforced denture base acrylic. *J Funct Biomater*. 2022;13(4):183. doi:10.3390/jfb13040183

42. Deb S, Muniswamy L, Thota G, et al. Impact of surface treatment with different repair acrylic resin on the flexural strength of denture base resin: an in vitro study. *J Contemp Dent Pract*. 2020;21(10):1137-1140.

43. Chladek G, Adeeb S, Pakieła W, Coto NP. Effect of different surface treatments as methods of improving the mechanical properties after repairs of PMMA for dentures. *Materials (Basel)*. 2024;17(13):3254. doi: 10.3390/ma17133254

44. Ariyani S, Chairunnisa R. The effect of surface treatment and thermocycling on bond strength between silicon soft denture lining and acrylic resin denture base. *J Pharmaceut Negat Res*. 2023:2943-2952. doi: 10.47750/pnr.2023.14.03.369

45. Karaokutan I, Ayvaz I. Effect of various surface treatments on relining bond strength of CAD-CAM denture base materials. *J Prosthodont*. 2024:1-7. doi:10.1111/jopr.13831

46. Klaiber D, Spintzyk S, Geis-Gerstorfer J, Klink A, Unkovskiy A, Huettig F. Bonding behavior of conventional PMMA towards industrial CAD/CAM PMMA and artificial resin teeth for complete denture manufacturing in a digital workflow. *Materials (Basel)*. 2021;14(14):3822. doi:10.3390/ma14143822

47. Kowalski R, Kozak BM, Sobolewska E. Contemporary hybrid acrylic materials and modern thermoplastics in the manufacture of dental prostheses. *Pomeranian J Life Sci*. 2023;69(1):39-45. doi:10.21164/pomjlifesci.904

48. Hakala P, Orell O, Sarlin E, Pääkkönen E, Jutila L, Kanerva M. Durability of sandwich structures with a maximized natural raw material basis: comparison of expanded polystyrene, cellulose foam and polylactic acid subjected to UV-rain aging. *Rakenteiden Mekaniikka*. 2023;56(1):24-40. doi:10.23998/rm.120756

49. Davies P, Le Gac PY, Le Gall M. Influence of sea water aging on the mechanical behaviour of acrylic matrix composites. *Appl Comp Mater*. 2017;24(1):97-111.

50. Al-Jmmal AY, Mohammed NZ, Al-Kateb HM. The effect of aging on hardness of heat cured denture base resin modified with recycled acrylic resin. *Clin Exp Dent Res*. 2024;10(1):e828. doi:10.1002/cre2.828

51. Rahaman Ali AAA, John J, Mani SA, El-Seedi HR. Effect of thermal cycling on flexural properties of microcrystalline cellulose-reinforced denture base acrylic resins. *J Prosthodont*. 2020;29(7):611-616. doi:10.1111/jopr.13018

52. Çakmak G, Donmez MB, Akay C, Abou-Ayash S, Schimmel M, Yilmaz B. Effect of thermal cycling on the flexural strength and hardness of new-generation denture base materials. *J Prosthodont*. 2023;32(S1):81-86. doi:10.1111/jopr.13615

53. Apimanchindakul C, Na Nan P, Aimjirakul N. Effect of reinforced self-cured acrylic resin on flexural strength. *Int J Dent*. 2022;2022:2698995. doi:10.1155/2022/2698995

54. Kondratiev A, Kochanov V, Yuresko T, Tsaritsynskyi A, Nabokina T. Durability of acrylic products during heat aging. *Solid State Phenomena*. 2022;334:145-153. doi:10.4028/p-8qo1zu

55. Paglia CS, Krattiger A. The dimensional stability and durability of acrylic resins for the injection of cementitious systems. *Eur J Formal Sci Engineer*. 2020;4(2):124-129.

56. White CC, Tan KT, Hunston DL, Forster AM, Jacobs DS. Impact of environmental factors on polymeric films used in protective glazing systems. *Serv Life Predict*. 2015:231-249. doi:10.1007/978-3-319-06034-7-1

57. Jang EJ, Hong YJ, Jeong YH, et al. In vitro antifungal and physicochemical properties of polymerized acrylic resin containing strontium-modified phosphate-based glass. *BMC Oral Health*. 2024;24(1):775. doi:10.1186/s12903-024-04547-5

58. AlEraky DM, Abuohashish HM, Gad MM, et al. The antifungal and antibiofilm activities of caffeine against *candida albicans* on polymethyl methacrylate denture base material. *Biomedicines*. 2022;10(9):2078. doi: 10.3390/biomedicines10092078

59. Alzayyat ST, Almutiri GA, Aljandan JK, et al. Antifungal efficacy and physical properties of poly(methylmethacrylate) denture base material reinforced with SiO2 nanoparticles. *J Prosthodont*. 2021;30(6):500-508. doi:10.1111/jopr.13271

60. Kachoei M, Divband B, Rahbar M, Esmaeilzadeh M, Ghanizadeh M, Alam M. A novel developed bioactive composite resin containing silver/zinc oxide (Ag/ZnO) nanoparticles as an antimicrobial material against *Streptococcus mutans*, *Lactobacillus*, and *Candida albicans*. *Evid Based Complement Alternat Med*. 2021;2021:4743411. doi:10.1155/2021/4743411

61. Robu A, Antoniac A, Grosu E, et al. Additives imparting antimicrobial properties to acrylic bone cements. *Materials (Basel)*. 2021;14(22):7031. doi:10.3390/ma14227031

62. Menikheim S, Leckron J, Duffy M, et al. Biocompatible nanocapsules for self-healing dental resins and bone cements. *ACS Omega*. 2022;7(36):31726-31735. doi:10.1021/acsomega.2c02080

63. Yan HY, Yang HY, Huang C. Advances of self-healing dental composite resin. *Chinese J Stomatol*. 2017;52(9):582-584. doi:10.3760/cma.j.issn.1002-0098.2017.09.016

64. Fugolin AP, Pfeifer CS. Strategies to design extrinsic stimuli-responsive dental polymers capable of autorepairing. *JADA Found Sci*. 2022;1:100013. doi:10.1016/j.jfscie.2022.100013

65. Ilyaei S, Sourki R, Haji Y, Akbari A. Capsule-based healing systems in composite materials: a review. *Critic Rev Solid State Mater Sci*. 2020;2021(6):491-531. doi:10.1080/10408436.2020.1852912

66. Harb SV, Trentin A, de Souza TAC, et al. Effective corrosion protection by eco-friendly self-healing PMMA-cerium oxide coatings. *Chemic Engineer J*. 2020;383:123219. doi:10.1016/j.cej.2019.123219