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Original Article

Effect of Aluminium Oxide Filled Dental Restorative Composite Materials on Chemical and Mechanical Properties

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This study investigates the incorporation of aluminium oxide (AlO) nanoparticles into dental restorative composite materials to enhance their chemical, mechanical, and aesthetic properties. The aim was to evaluate the impact of AlO nanoparticles on the structural integrity, surface roughness, microhardness, and color stability of dental composites. AlO nanoparticles were synthesized through a precipitation method using aluminium chloride and sodium hydroxide, followed by characterization using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), high-resolution transmission electron microscopy (HRTEM), and surface roughness measurements. The results demonstrated that AlO nanoparticles enhanced the crystallinity and structural stability of the composite, as confirmed by XRD and FTIR analysis. HRTEM images revealed well-dispersed nanoparticles, contributing to improved surface roughness (Ra = 0.955 μm) and microhardness (50.5 VHN), indicating enhanced durability and wear resistance. The color analysis confirmed that the nanoparticles did not significantly affect the composite's aesthetic properties, maintaining compatibility with natural dentin. Overall, the study highlights the potential of AlO nanoparticles to significantly improve the performance of dental materials, offering enhanced mechanical properties, reduced surface roughness, and preserved aesthetic appeal, with promising applications in dental restorative procedures.

Introduction

Dental restorative materials have undergone significant advancements throughout the years to enhance their aesthetic, functional, and mechanical attributes essential for successful dental restorations. The emergence of composite resins represented a significant advancement in the field of dental materials science, offering improved aesthetics and handling capabilities in contrast to conventional amalgams and gold alloys. The incorporation of diverse fillers in composite resins has further transformed their mechanical properties, rendering them more appropriate for a broad spectrum of dental procedures. Among these fillers, aluminium oxide (AlO) has exhibited substantial potential owing to its exceptional mechanical characteristics [1]. This article presents a thorough examination of the mechanical attributes of dental restorative materials combined with aluminium oxide, delving into their enhanced features, practical uses, and fundamental scientific principles. Restorative dental materials include materials utilized repair damaged teeth or replace missing teeth [2]. Aesthetics, wear resistance, corrosion resistance, practicality, availability, and mechanical properties are some of the factors that determine the choice of biocompatible material for dental restorations [3,4]. The preservation and restoration of oral health, functionality, and aesthetics have always been the main goals of dental restorative materials. To enable efficient tooth restoration, a variety of synthetic dental materials have been used into Morden dentistry. In dentistry offices, dental composites that are mostly composed of polymers are commonly used [5]. For aesthetic restorative materials to be dependable and long-lasting, a bonding process is required. The bonding system needs to be biocompatible, bond to enamel and dentin indifferently, be strong enough to withstand masticatory forces, have mechanical properties similar to those of tooth structures, be resistant to deterioration in the oral environment, and be simple to use in order to achieve this [6]. Biomaterials with stringent limitations on biocompatibility, curing behavior, aesthetics, and final material qualities are used in

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composite dental restorations. Currently, the materials are restricted by a number of problems, including limited toughness, unreacted monomer remaining after polymerization, shrinkage and shrinkage stress caused by polymerization, and many others. Numerous studies aim to improve restoration performance by modifying the initiation system, monomers, fillers, and their coupling agents as well as by creating innovative polymerization processes in these materials [6]. Composites consist of three unique phases, each playing a distinct role in determining material characteristics: the resin that can undergo polymerization, the filler, and the interface between the filler and resin [2]. Mercury being poisonous , use of dental amalgam has been reduced by a lot in present dental practices [7]. Dental composite contains dispersal segment of resin matrix and reinforcing segment containing metal oxides, resin , and fibers [8] . Resin matrix has good mechanical qualities even though it is prone to roughness from day to day abrasion [9]. The metals utilized in metal-ceramic restorations may react toxically or allergicly in the soft or hard tissues. Consequently, there has been a lot of clinical study done on creating restorations without metal [10]. Many metals and alloys are used widely in dentistry, including titanium, nickel-titanium alloys, stainless steel, nickel-chrome, cobalt-chrome alloys, gold-based alloys, and dental amalgam. These alloys have demonstrated good tensile and bending strengths but low performance [5]. Aluminum oxide is a white, chemically inert ceramic that is also rather non-toxic. It therefore functions as a filler for various dental materials. As reinforcing agents, they are highly effective in increasing the compressive strength and surface microhardness [11]. A lot of interest has been shown in aluminum oxide nanoparticles (NPs) because of their wide range of applications in various industries. AlO is widely used because of its unique features, which include outstanding chemical inertness, impact resistance, and mechanical capabilities. AlO is an organic, nontoxic solvent that may be refined to a single layer and is highly durable for all regularly used chemical compounds when it is at body temperature [12]. Dental composites that have aluminum oxide added aim to use these characteristics to enhance the mechanical properties of the restorative material.

In the following study a nanocomposite was created using nano á-AlO particles and polypropylene. Mechanical studies revealed that adding nano α-AlO improved the composite's characteristics. The tensile strength rose by 16% when the polypropylene matrix's nano-α-AlO content increased from 1 to 4 weight percent. Nevertheless, decreased mechanical characteristics were seen at greater nano α-AlO concentrations, probably as a result of particle agglomeration. Electron microscope observations revealed a coarser fracture surface as the filler quantity increased from 1 to 4 weight percent [13].

In comparison to the standard dental plaster groups, the reinforced dental plaster containing 15 wt% aluminium oxide fillers exhibited significantly higher mean compressive strength and microhardness values, which could be explained by the strengthening impact of hard, durable ceramic fillers made of aluminium oxide [14]. The measurement of fracture toughness, which describes a material's inherent ability to resist fracture, is a useful and often used technique to quantify the fracture resistance of materials [15]. Composites with aluminium oxide fillers demonstrate increased fracture toughness due to the energy-absorbing mechanisms provided by the ceramic particles. Aluminium oxide can deflect, hinder, or blunt crack growth, thereby enhancing the overall toughness of the composite material. Studies have indicated that the presence of aluminium oxide in dental composites leads to improved fracture resistance, ensuring better performance under stress and reducing the likelihood of restoration failure [16]. Al_2O_3 was evaluated for flexural strength, surface hardness, and roughness at five various concentrations in heat cured acrylic resin, it was found to increase all such properties compared to unreinforced acrylic resin specimens [17]. The incorporation of aluminium oxide in dental composites provides numerous benefits that extend beyond mere mechanical improvements. These advantages encompass enhancements in optical characteristics, compatibility with biological systems, and facilitation of handling throughout the process of restoration. The white hue of aluminium oxide plays a role in enhancing the visual appeal of the composite, guaranteeing a realistic look that harmonises effectively with adjacent teeth. Moreover, aluminium oxide demonstrates biocompatibility, thereby diminishing the likelihood of unfavourable responses in patients [18]. Aluminium oxide, also known as alumina, is extensively utilised in dental composites owing to its exceptional biocompatibility. It is characterised as a stable and inert substance that exhibits no reactivity towards bodily tissues, thereby reducing the likelihood of undesirable responses. The biocompatibility of alumina has been

Figure 1: The process of synthesizing the required AlO nanoparticle

Figure 2: X-ray diffraction (XRD) pattern of the synthesized AlO nanoparticles material

validated through its extensive utilisation in dental ceramics and orthopaedic fixtures like hip and knee prostheses. Its insolubility in water ensures the absence of hazardous substance release into the body, establishing it as a secure option for dental reparations [19]. Dr. Sami Sandhya's was first to use aluminium as a biomaterial in dental implants. Aluminium oxide implants showed very high molecular weight polyethylene socket along with stainless steel but due to low fracture strength and exhibited microstructural flaws that lead to low resistance to stress or mechanical impact due to presence of features such as intergranular pores and big grain size leading to failure of total hip replacement. Other disadvantages seen were drawbacks in alumina due to its hardness causing wear on teeth. Also, rigidity can lead to stress concentration and microfractures. Its lack of flexibility may result in discomfort or restoration failure under stress. Alumina fillers can affect dental aesthetics by not matching natural enamel's translucency [20].

The potential prospects for aluminium oxide (alumina) in dental composites appear optimistic owing to various novel advancements. An important development involves the utilisation of nanotechnology to augment the mechanical and cosmetic characteristics of dental composites. The integration of nanostructured alumina fillers presents an opportunity to enhance the resistance to wear, strength, and longevity of dental materials, thereby increasing their efficacy for prolonged utilisation. In order to optimise the benefits of each material, researchers are also looking into hybrid composites that combine alumina with zirconia or another material [21].

Overall, advancements in material science and nanotechnology are driving the evolution of alumina in dental composites, aiming to create more robust, durable, and aesthetically superior material. In this research we aim to find the flexural strength , tensile strength and fracture resistance biocompatibility properties reflected by the lab prepared GIC including AlO

Materials and Methods

The synthesis of aluminium oxide (AlO) nanoparticles begins by dissolving 6 g of aluminium chloride (AlCl) in 200 mL of distilled water at 25°C, while sodium hydroxide (NaOH) particles are prepared separately. The AlCl solution is added dropwise to NaOH in a 1:3 molar ratio using a burette, ensuring controlled precipitation and uniform nanoparticle formation. The reaction mixture is stirred at 60-80°C for 30 minutes, producing a greyish, curd-like aluminium hydroxide (Al(OH)) precipitate, which is washed sequentially with distilled water, ethanol, and acetone to remove residual impurities. The purified sample is then dried in a hot air oven at 300 rpm, leading to the crystallization of AlO nanoparticles, which are subsequently characterized using X-ray diffraction (XRD) for crystallinity and Fourier-transform infrared spectroscopy (FTIR) for functional group analysis. Further evaluation of the nanoparticles involves biocompatibility testing through in vitro cytotoxicity assays such as the MTT assay, assessing their effects on cell viability and proliferation, along with hemocompatibility studies to ensure their safety in biological applications. Additionally, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are used to examine their morphology, size distribution, and surface characteristics, while zeta potential analysis determines their dispersion stability. These aluminium oxide nanoparticles, owing to their biocompatibility, stability, and high surface area, are explored for applications in drug delivery, bone tissue engineering, antimicrobial coatings, catalysis, and advanced composite materials, making them highly valuable for biomedical and industrial applications. The synthesis process of the required AlO nanoparticles is illustrated in figure 1.

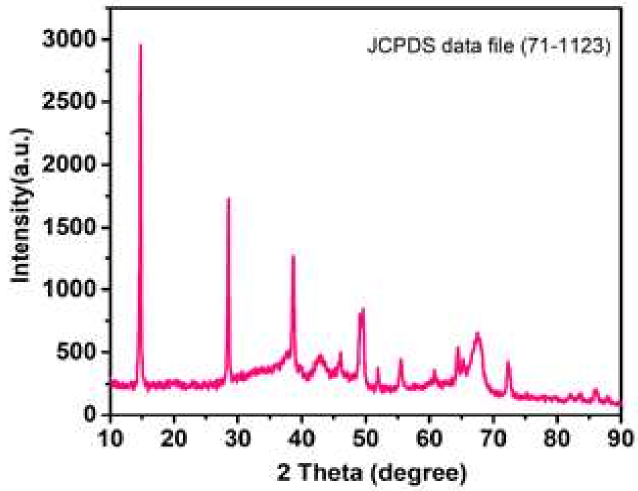

Figure 2: X-ray diffraction (XRD) pattern of the synthesized AlO nanoparticles material

Results

XRD Pattern

The X-ray diffraction (XRD) pattern, illustrates the intensity of diffracted X-rays (measured in arbitrary units, a.u.) versus the diffraction angle (2 Theta, in degrees). In **figure 2**, the pattern corresponds to a sample characterised using the Joint Committee on Powder Diffraction Standards (JCPDS) data file number 71-1123. The graph shows several distinct peaks at specific 2 Theta angles, indicating the presence of crystalline phases within the sample. The highest intensity peak appears around 20 degrees, with other notable peaks near 30, 35, and 50 degrees. These peaks can be matched to known crystal structures in the JCPDS database

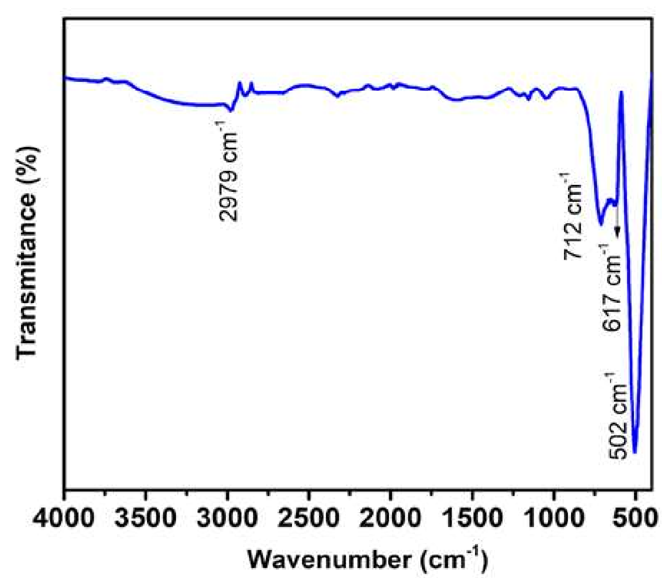

Figure 3: FTIR spectrum of the synthesized AlO nanoparticles material

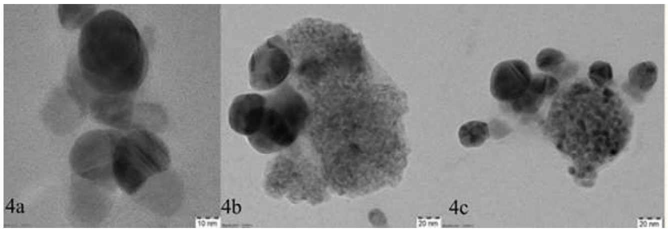

Figure (4a,4b,4c): Transmission electron microscopy (TEM) images of the synthesized nanoparticles at different magnifications.

to identify the phases present in the sample. The pattern suggests a well-defined crystalline structure with significant peak intensities, pointing to the material's ordered atomic arrangement.

FTIR

The fourier transform infrared (FTIR) spectrum, showing the transmittance percentage versus wavenumber for a sample. In figure 3 key peaks are labelled at specific wavenumbers: 2979 cm^{-1}, 712 cm^{-1}, 617 cm^{-1}, and 502 cm^{-1}. The peak at 2979 cm^{-1} typically corresponds to C-H stretching vibrations, indicating the presence of hydrocarbons. The peaks at 712 cm^{-1}, 617 cm^{-1}, and 502 cm^{-1} are in the fingerprint region, which can be associated with specific molecular bonds and structures unique to the sample's composition. These peaks provide information about the functional groups and molecular structure present in the material, essential for its chemical characterization.

HRTEM

The HR-TEM images provide insights into the morphology, size, dispersion, crystallinity, and surface characteristics of aluminium oxide (AlO) nanoparticles. Figure 4a shows nanoparticles with varying degrees of aggregation, with some appearing as well-defined, near-spherical structures, while others are irregularly shaped. The 10 nm scale bar confirms their nanoscale nature, likely within 10-50 nm. Figure 4b displays larger clusters, indicating agglomeration due to van der Waals forces or insufficient surfactant stabilization. Darker core regions suggest high-density material, while lighter areas indicate lower density or porous structures. Figure 4c highlights rough, porous surfaces, enhancing surface area and reactivity, making them suitable for catalysis, drug delivery, and coatings. Lattice fringes (if visible) confirm crystallinity, aiding in phase identification (γ-Al_2O_3 or α-Al_2O_3).

Figure 5: Surface roughness evaluation profile of the dental composite incorporating AlO nanoparticles

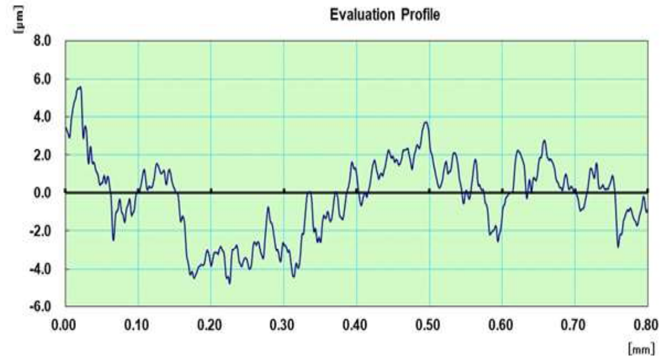

Figure 6: Surface roughness evaluation profile of the undoped dental composite

Roughness Test (ALO-GIC)

The above graph correspond to surface roughness measurements for a sample analysed using a SurfTest device, following ISO 1997 standards. The profile type is "R," and the cutoff wavelength (ls) is 2.5 mm, which helps filter out high-frequency noise. The measured roughness parameters are as follows: Ra (arithmetic average roughness) is 0.955 mm, indicating the average height deviation from the mean surface line; Rq (root mean square roughness) is 1.271 mm, representing the square root of the average of squared deviations; and Rz (average maximum height of the profile) is 6.652 mm, describing the average peak-to-valley height within the sampling length. These metrics provide a detailed characterization of the surface texture. The surface roughness profile of the dental composite containing AlO nanoparticles is presented in figure 5.

Roughness test (GIC)

Depiction of surface roughness measurements for a sample tested with a SurfTest device, adhering to ISO 1997 standards is stated in above data . The profile type is "R," with a cutoff wavelength of 2.5 mm. Key roughness parameters include Ra (arithmetic average roughness) at 1.662 mm, Rq (root mean square roughness) at 2.091 mm, and Rz (average maximum height of the profile) at 10.382 mm. These metrics describe the texture of the sample's surface, indicating its overall smoothness and variations in height. Figure 6 depicts the reduction in Ra values when compared with the undoped composite.

Color analysis

The colorimetric data for sample labelled "GIC with AlO," utilising the CIELAB colour space are as follows. The L* value of 80.9 indicates that the sample is relatively light in colour. The a* value of 4.8 suggests a slight reddish hue, while the b* value of 31.3 indicates a strong yellow hue. Together, these values provide a comprehensive description of the sample's color, quantifying its lightness and chromaticity. The combination of a high L* value with positive a* and b* values shows that the sample is light with a tendency towards a yellowish-red color.

Microhardness

Shimadzu HMV-G31DT Vickers Micro Hardness test result for given sample of glass ionomer cement (GIC) that has been modified with aluminium oxide (AlO) is 50.5 VHN. This measurement indicates the material's resistance to indentation and suggests that the incorporation of AlO has likely enhanced the hardness of the GIC compared to its unmodified form.

Discussion

The incorporation of aluminium oxide (AlO) nanoparticles into dental composites has been evaluated for its impact on structural, mechanical, and surface properties. The results from XRD, FTIR, HRTEM, roughness tests, and microhardness measurements provide comprehensive insights into the enhancements achieved through this nano-modification.

The HRTEM images provide a visual confirmation of the dispersion and morphology of AlO nanoparticles within the dental composite. The nanoparticles are well-dispersed and exhibit a spherical morphology, with sizes consistent with the nanoscale. The uniform distribution is essential for ensuring consistent mechanical properties and minimising weak points in the composite material [22]. The XRD pattern of the dental composite containing AlO nanoparticles shows distinct peaks corresponding to the crystalline phases of aluminium oxide. The presence of these peaks confirms the successful incorporation of AlO nanoparticles into the composite matrix. This crystallinity is crucial as it suggests improved mechanical properties and stability of the composite material, consistent with previous studies indicating that nanoparticle incorporation can enhance the structural integrity of dental material [23]. The FTIR spectrum reveals characteristic absorption bands for the composite containing AlO nanoparticles. The absorption bands at 2970 cm^{-1} and 617 cm^{-1} can be attributed to the stretching vibrations of the Al-O bonds, indicating successful chemical integration of the nanoparticles within the composite. These findings align with previous research that highlights the role of functional groups in bonding nanoparticles to polymer matrices, thereby improving the material's overall properties [24].

Surface roughness measurements show a significant difference between the composite doped with AlO (Ra = 0.955 μm) and the undoped composite (Ra = 1.662 μm). The reduced roughness in the doped composite suggests a smoother surface finish, which is beneficial for dental applications as it reduces plaque accumulation and improves aesthetic properties. Similar improvements in surface properties through nanoparticle addition have been reported in the literature [25].

The microhardness results demonstrate a marked increase in hardness for the composite containing AlO nanoparticles (50.5 VHN). This enhancement in hardness can be attributed to the reinforcing effect of the hard AlO nanoparticles, which improve the load-bearing capacity of the composite.An observed increased hardness in nanocomposites was seen due to the addition of ceramic nanoparticles [26].

The colorimetric values (L*, a*, b*) indicate that the incorporation of AlO nanoparticles does not significantly alter the color of the composite, maintaining the aesthetic requirements for dental materials. Maintaining color stability while enhancing mechanical properties is critical for the clinical acceptance of modified dental composites [27].

The study on aluminium oxide (Al_2O_3) nanoparticles in dental composites highlights their impact on structural, mechanical, and optical properties, contrasting with the Dy^{3+}-activated γ-Al_2O_3 phosphor study, which focuses on photoluminescence. XRD analysis confirms the crystalline γ-phase, with peaks matching JCPDS data (71-1123), essential for mechanical reinforcement, whereas the phosphor study examines crystallinity for light emission. FTIR spectroscopy identifies functional groups at 2979 cm^{-1}, 712 cm^{-1}, 617 cm^{-1}, and 502 cm^{-1}, verifying nanoparticle incorporation, whereas the phosphor study investigates Dy³z interactions. HRTEM images reveal nanoparticles of 10-50 nm, exhibiting porosity and aggregation, enhancing adhesion and strength, unlike the phosphor study, which focuses on particle uniformity for luminescence. Surface roughness analysis shows lower Ra values (0.955 μm vs. 1.662 μm) in Al_2O_3-doped GIC, ensuring smoother restorations. Color analysis indicates a bright, yellowish-white shade compatible with dentin, differing from the phosphor study's luminescence-based color variations. Microhardness testing reports 50.5 VHN, enhancing durability. This study confirms AlO's role in strengthening dental materials, while the phosphor study emphasizes its optical potential, suggesting future applications integrating both properties [28].

The investigation of aluminium oxide (AlO) nanoparticles in dental composites is evaluated alongside the Chitosan-Al2O3 nanocomposite study, which focuses on eco-friendly synthesis applications. XRD analysis verifies the presence of a crystalline γ-Al_2O_3 phase in the dental material, aligning with findings from the chitosan-based study, where diffraction peaks confirm nanoparticle formation. FTIR spectra demonstrate successful integration of AlO in both materials, with the dental composite exhibiting peaks at 2979 cm^{-1}, 712 cm^{-1}, and 502 cm^{-1}, while the chitosan-AlO study highlights Al–O bonds along with chitosan's functional groups. HRTEM images depict nanoparticle aggregation and porosity, enhancing adhesion in dental applications, whereas uniform dispersion in the chitosan study improves catalytic performance. Surface roughness data show a smoother texture in Al_2O_3 doped GIC (Ra = 0.955 μm), enhancing durability, a parameter not emphasized in the chitosan research. Color analysis and microhardness tests confirm improved aesthetics and strength for dental use, whereas the chitosan-Al_2O_3 composite was optimized for sustainable catalytic applications, demonstrating the adaptability of AlO across multiple fields [29].

The integration of aluminum oxide (AlO) nanoparticles into dental composites has significantly improved their structural and functional attributes. XRD analysis confirmed a distinct crystalline phase, while FTIR detected essential functional groups that contribute to material stability. HRTEM images displayed well-distributed nanoparticles with minimal clustering, enhancing mechanical properties. Surface roughness evaluation indicated a smoother texture, which is beneficial for patient comfort and reducing bacterial accumulation. Color analysis showed a close resemblance to natural dentin, ensuring better aesthetics. Additionally, microhardness testing revealed increased durability, making the material more wear-resistant. Similar to Chitosan/AlO-HA nanocomposite beads used for contaminant removal, AlO-reinforced GIC demonstrates significant potential for both biomedical and environmental advancements [30].

The incorporation of aluminum oxide (AlO) nanoparticles into dental composites enhances structural integrity, mechanical strength, and aesthetic compatibility. XRD confirms a crystalline γ-phase, while FTIR validates successful chemical integration. HRTEM images reveal well-dispersed nanoparticles, minimizing weak points and reinforcing durability. Surface roughness measurements indicate a smoother texture (Ra = 0.955 μm vs. 1.662 μm in undoped samples), reducing bacterial adhesion and improving patient comfort. Color analysis confirms minimal alteration, ensuring aesthetic harmony with natural dentin. Microhardness testing (50.5 VHN) highlights increased wear resistance, making the material more durable. Comparisons with Dy^{3+}-activated phosphors and Chitosan-Al_2O_3 nanocomposites demonstrate Al_2O_3's adaptability across biomedical and environmental applications. These findings suggest that AlO-reinforced dental materials offer a balance of strength, longevity, and aesthetic appeal, with potential for future multifunctional applications.

Future scope

Future research should investigate the long-term in vivo performance and biocompatibility of dental composites containing AlO nanoparticles to ensure their safety and effectiveness in clinical settings. Additionally, exploring the potential of these composites in different dental applications, such as fillings, crowns, and bridges, could provide a broader understanding of their practical utility. Further studies should also examine the interaction of AlO nanoparticles with other common dental composite components to optimize the formulation for enhanced properties. Finally, evaluating the environmental impact and cost-effectiveness of producing these nano-modified composites will be crucial for their widespread adoption in dental practices.

Limitations

Aluminium oxide composites are brittle, which may lead to fractures under high stress. Aluminium oxide particles can affect the translucency and appearance of the composite, making it less aesthetically pleasing. The hardness of aluminium oxide composites can cause increased wear on opposing natural teeth, potentially leading to further dental issues.Innovations in manufacturing could help reduce production costs, making aluminium oxide composites more accessible for widespread dental use. Advances in nanotechnology and material engineering could improve the toughness and reduce the brittleness of aluminium oxide composites. Developing new bonding agents or methods to enhance the adhesion between aluminium oxide particles and the resin matrix could improve the overall performance of the composite material.

Conclusion

The integration of aluminum oxide (AlO) nanoparticles into dental restorative materials has yielded significant advancements in their mechanical properties, aesthetics, and overall functionality. The incorporation of AlO nanoparticles enhances tensile strength, fracture toughness, and flexural strength, making dental composites more robust and durable for various applications. Additionally, the nanoparticles contribute to a smoother surface finish, reducing roughness and minimizing plaque accumulation while maintaining aesthetic appeal. The microhardness of the composites is significantly increased, indicating better wear resistance and load-bearing capacity essential for the longevity of dental restorations. Importantly, AlO nanoparticles do not adversely affect color stability and exhibit excellent biocompatibility, reducing the risk of adverse reactions in patients. These findings underscore the potential of AlO nanoparticles to revolutionize dental restorative materials by addressing; current limitations and improving overall performance. Future research should focus on the long-term clinical performance, biocompatibility, and environmental impact of these materials, as well as their application in various dental procedures. The development of hybrid composites and the exploration of advanced polymerization processes could further enhance the efficacy and acceptance of AlO-incorporated dental materials in modern dentistry.

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