ZINC-BASED DENTAL CEMENTS: PROPERTIES, APPLICATIONS, AND ADVANCEMENTS

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ABSTRACT

Aim of the study Zinc-based dental cements have played a significant role in restorative dentistry for several decades. These cements, including zinc phosphate, zinc oxide-eugenol (ZOE), and zinc polycarboxylate, offer unique properties and have been utilized in various clinical applications. **Material and methods** We performed an extensive exploration of pertinent scientific literature to gather information for the present review. Systematic searches were executed in electronic databases, such as PubMed, Google Scholar, and Web of Science, targeting articles released from April. The scope of the search focused on articles written exclusively in the English language. The search encompassed a comprehensive set of keywords and their various combinations, including "zinc-based dental cements," "properties," "applications," "advancements," "biocompatibility," "adhesion," "mechanical strength," "temporary restorations," "luting agents," "dental materials," and "clinical outcomes." **Results** zinc-based dental cements have demonstrated their significant potential as versatile materials in modern dentistry. Through a comprehensive exploration of their properties, applications, and advancements, it is evident that these cements offer a wide range of benefits for both practitioners and patients. **Conclusions** As research and development efforts persist, it is foreseeable that zinc-based dental cements will continue to evolve, further solidifying their role as integral components of successful dental treatments. With their ever-expanding applications and consistent improvements, these cements contribute significantly to the advancement of dental care, benefiting both practitioners and patients alike.

Key words: dental cements, zinc oxide, zinc phosphate

INTRODUCTION

Zinc-based dental cements have been widely used due to their desirable properties, including good biocompatibility, ease of manipulation, and adequate mechanical strength. This article aims to review the composition and properties of zinc-based dental cements, as well as their clinical applications in restorative dentistry. Furthermore, recent advancements in the field and potential areas for further research are discussed.

MATERIAL AND METHODS

Selection of Literature.

A comprehensive search of scientific databases (e.g., PubMed, Scopus, Web of Science) was conducted to identify relevant articles and reviews related to zinc-based dental cements. Keywords used for the search included "zinc-based dental cements," "zinc oxide eugenol cement," "zinc phosphate cement," "zinc polycarboxylate cement," "zinc oxide-based cement," and "dental cement properties and applications."

Inclusion criteria: Articles published in peer-reviewed journals, written in English, and focusing on the properties, applications, and advancements of zinc-based dental cements.

Data Extraction.

Relevant data from the selected articles were extracted and organized based on the following key aspects: Cement composition: Types and proportions of zinc-based cements, including zinc oxide eugenol cement, zinc phosphate cement, zinc polycarboxylate cement, and other zinc oxide-based cements. Physical properties: Setting time, compressive strength, film thickness, solubility, radiopacity, and other relevant physical characteristics of the cements. Mechanical properties: Flexural strength, bond strength, wear resistance, and other mechanical properties of the cements. Biocompatibility: Evaluation of the cytotoxicity, tissue response, and biocompatibility of the cements. Clinical applications: Overview of the various applications of zinc-based dental cements, such as temporary fillings, luting agents, pulp-capping materials, and root canal sealers. Advancements and innovations: Recent developments, novel formulations, and emerging trends in zinc-based dental cements.

Data Analysis.

The extracted data were synthesized and analyzed to provide an overview of the properties, applications, and advancements of zinc-based dental cements. Key findings, trends, and advancements were identified and discussed in the review. Gaps in the current knowledge or areas requiring further research were highlighted.

Writing the Review.

The review paper was structured based on the analysis of the extracted data. The sections of the review, such as Introduction, Materials and Methods, Results, Discussion, and Conclusion, were drafted based on the key aspects identified during data analysis. Relevant citations and references were included to support the findings and statements made in the review.

Review and Revision.

The draft of the review paper was thoroughly reviewed and revised for clarity, coherence, and accuracy. Feedback from co-authors, supervisors, or experts in the field was incorporated to strengthen the review.

Results and DISCUSSIONS

Zinc compounds have gained significant attention in dental medicine due to their versatile properties and applications. This review provides a comprehensive overview of the various zinc compounds used in dental practice, focusing on their characteristics, mechanisms of action, and clinical applications. The aim is to consolidate the existing knowledge on zinc compounds and their potential in modern dental medicine. Properties and characteristics of zinc oxide, including its antibacterial, antifungal, and anti-inflammatory effects. Clinical applications of zinc oxide in dental materials, such as temporary fillings, cements, and impression materials. Overview of zinc phosphate cements, including their composition, setting reaction, and physical properties. Clinical applications of zinc phosphate cements in restorative dentistry, such as crown and bridge cementation, liners, and bases. Properties and applications of zinc polycarboxylate cements, emphasizing their adhesive and biocompatible characteristics. Discussion of the antimicrobial and astringent properties of zinc chloride. Applications of zinc chloride in periodontal treatments and dental materials. Examination of zinc-based antimicrobial agents, such as zinc ions and zinc nanoparticles, for their potential use in oral healthcare. Evaluation of their antibacterial, antifungal, and antiviral properties and their application in preventive dentistry and restorative procedures.

Zinc phosphate cement, one of the earliest zinc-based cements, is composed of zinc oxide powder, magnesium oxide, and polyacrylic acid. It exhibits good mechanical properties and adequate biocompatibility. However, its low solubility and lack of adhesive properties limit its long-term use. Zinc oxide-eugenol cement (ZOE) consists of zinc oxide powder, eugenol, and accelerators. ZOE cement offers antimicrobial properties and provides temporary restorations with ease of manipulation. However, its solubility, lack of adhesive strength, and potential pulp irritation have restricted its permanent use. Zinc polycarboxylate cement incorporates a powder containing zinc oxide, magnesium oxide, aluminum oxide, and bismuth, along with polyacrylic acid [2]. This cement exhibits better adhesive properties and biocompatibility compared to zinc phosphate and ZOE cements. Nevertheless, its solubility, poor mechanical properties, and opaque esthetics have limited its long-term utilization.

Dental cements, also known as luting agents, are adhesive materials commonly used in the final stage of clinical procedures. Their purpose is to fill the gap between indirect restorations and prepared teeth while creating a bond between them during the necessary timeframe. This cementation or polymerization process, referred to as the setting process, ensures a secure bond between the tooth and the restoration, effectively holding the latter in place indefinitely and forming an impenetrable seal between the tooth and the adjacent restoration. Over the years, various types of dental cements have been utilized in dentistry applications[3].

In the literature, there are numerous studies investigating the properties and applications of dental cements. These studies explore the impact of different factors such as composition, particle size, and curing mechanisms on the performance and longevity of dental restorations. Furthermore, researchers have focused on improving the bond strength, marginal integrity, and aesthetics of dental cements through innovative formulations and techniques. Continued advancements in dental cement technology aim to provide clinicians with reliable and long-lasting solutions for various dental procedures[6, 36].

In dentistry, dental cements serve a crucial role in attaching the restoration material to the tooth tissue. This attachment is achieved through three distinct mechanisms. The first mechanism involves micromechanical interlocking that occurs between the rough surfaces of acid-etched teeth, the cements, and the restoration. It is important to note that the luting mechanism of dental cements relies primarily on non-adhesive, micromechanical retention, which is supplemented by molecular adhesion resulting from bipolar van der Waals forces and weak chemical bonds between the cements and the tooth. This mechanism forms the fundamental basis for the retention of dental cements. Techniques such as air abrasion and acid etching further enhance the micromechanical bonding by increasing the surface irregularities of these cements, particularly when using resin and resin-modified glass ionomer cements[7].

Moreover, studies in dental literature have investigated various surface treatment methods to optimize the micromechanical bonding of dental cements. Air abrasion, which involves the use of abrasive particles propelled by compressed air, can create a roughened surface on the tooth enamel, increasing the surface area for bonding and improving the retention of dental cements. Acid etching, on the other hand, involves the application of an acidic solution to the tooth surface, resulting in the removal of the smear layer and creating microirregularities that enhance the mechanical interlocking between the tooth, cement, and restoration.

In recent years, there have been advancements in dental cement formulations to enhance adhesive properties and optimize bonding strength. Resin and resin-modified glass ionomer cements have gained popularity due to their improved adhesion and bonding capabilities. These materials incorporate resin components that can chemically bond to the tooth structure, leading to enhanced retention and durability of the restorations.

Overall, dental cements play a critical role in ensuring the long-term success and stability of dental restorations. Ongoing research and advancements in surface treatment techniques and cement formulations continue to contribute to the development of more reliable and effective bonding agents in dentistry [4].

The literature provides various classifications of dental cements, each based on different criteria. Craig [3, 43] classified dental cements according to their clinical usage into two categories: definitive and provisional (temporary) cements. Definitive cements are used for permanent bonding of restorations to teeth for long-term retention, while provisional cements are employed for shorter periods, facilitating the completion of permanent restorations. Temporary cements include zinc oxide-eugenol (ZOE), zinc oxide non-eugenol, and calcium hydroxide cements. Definitive cements, on the other hand, are further divided into three groups based on their adhesive potential: low (zinc phosphate, silicate cements), medium (polycarboxylate cements), and high (glass ionomer cements). Sunico Segarra et al. proposed a classification of dental cements into conventional luting cements (such as zinc phosphate, polycarboxylate, glass ionomer, and resin-modified glass ionomer) and bonding cements (resin cements). Additionally, Powers and Wataha [33] categorized cements into water-based (e.g., glass ionomer cements, resin-modified glass ionomer cements, zinc polycarboxylate, and zinc phosphate), oil-based (zinc oxide-eugenol), and resin-based (adhesive resin, self-adhesive resin, and esthetic resin) cements. Another classification system, proposed by O'Brien, is based on the type of matrix bond and includes phosphate-bonded, phenolate, polycarboxylate, resin, and resin-modified glass ionomer cements[8, 44].

These classifications reflect the diverse nature and functions of dental cements, allowing clinicians to choose the most suitable type for specific applications. Each category of dental cement offers unique properties, such as adhesion strength, durability, and esthetics, which can influence the success and longevity of dental restorations. Advances in cement technology continue to expand the range of available options, providing clinicians with a wide selection of materials to meet various clinical needs [7].

The following table presents an overview of various cement types used in dental applications, including their compositions, indications, advantages, and disadvantages. Dental cements play a crucial role in restorative dentistry, providing retention, support, and sealing properties for various dental procedures. Understanding the characteristics of different cement types is essential for selecting the most appropriate material based on specific clinical indications and patient needs. The table 1 aims to provide a concise summary of the key features of each cement type, assisting dental professionals in making informed decisions regarding their clinical use. By evaluating the composition, indications, advantages, and disadvantages of each cement type, dental practitioners can determine the most suitable option for achieving successful treatment outcomes while considering the inherent strengths and limitations of each material.

Table 1. Evaluating the composition, indications, advantages, and disadvantages of each cement type.

Cement Type	Composition	Indications	Advantages	Disadvantages
Zinc Phosphate Cement	Zinc oxide powder, Phosphoric acid liquid	Permanent cementation of crowns, bridges	High strength, good retention	High acidity, potential pulp irritation
Zinc Polycarboxylate Cement	Zinc oxide powder, Polyacrylic acid liquid	Permanent cementation, Orthodontic bands	Biocompatible, good adhesion	Limited strength, technique-sensitive
Zinc Oxide Eugenol Cement	Zinc oxide powder, Eugenol liquid	Temporary cementation, Pulp capping	Sedative effect, good thermal insulation	Weaker than other cements, potential allergic reactions
Zinc Oxide Non-Eugenol Cement	Zinc oxide powder, Non-eugenol liquid	Temporary cementation, Pulp capping	Comparable strength to eugenol cement, reduced allergic reactions	Longer setting time, technique-sensitive
Zinc Phosphate Reinforced Glass Ionomer Cement	Zinc oxide powder, Polyalkenoic acid liquid, Glass fillers	Restorative material, Cementation	Improved esthetics, fluoride release	Lower strength compared to other cements
Zinc Oxide Eugenol Reinforced Glass Ionomer Cement	Zinc oxide powder, Eugenol liquid, Polyalkenoic acid liquid, Glass fillers	Restorative material, Pulp capping	Better strength than eugenol cement, fluoride release	Potential allergic reactions, technique-sensitive

Cement Type	Composition	Indications	Advantages	Disadvantages
Zinc Oxide Non-Eugenol Reinforced Glass Ionomer Cement	Zinc oxide powder, Non-eugenol liquid, Polyalkenoic acid liquid, Glass fillers	Restorative material, Pulp capping	Comparable strength to non-eugenol cement, reduced allergic reactions	Longer setting time, technique-sensitive

Zinc Phosphate Cements

Zinc phosphate, a water-based dental cement, was initially introduced in 1879 for the permanent cementation of indirect restorations. Over the past century, the formulation of this cement has undergone modifications, and it is now widely regarded as a gold standard in dentistry [9, 40]. Zinc phosphate cement is known for its affordability and non-adhesive nature, making it suitable for use with metals, metal-ceramics, and ceramics. It typically attains its maximum physical properties after a curing period of 24 hours[10, 45].

In addition to its traditional use as a luting cement, zinc phosphate has found applications in other dental procedures. It has been utilized as a base or liner material due to its biocompatibility and ability to stimulate the formation of secondary dentin. The cement's alkaline pH and the release of calcium ions from its structure contribute to this bioactivity [16].

Despite its widespread use, zinc phosphate cement does have limitations. Its lack of adhesive properties necessitates the reliance on mechanical retention for restoration stability. Furthermore, the cement's high acidity during the initial setting phase can potentially cause pulpal irritation and compromise the longevity of restorations. As a result, newer generations of dental cements, such as resin-based cements, have been developed to address these shortcomings and provide improved bonding and aesthetics.

The literature reveals ongoing research efforts to enhance the properties of zinc phosphate cement. Various modifications to its composition and the addition of materials such as glass fibers and nanoparticles have been explored to improve its mechanical strength, biocompatibility, and adhesive capabilities [12, 38]. Additionally, studies have investigated the effect of different surface treatments on the bond strength between zinc phosphate cement and various substrates, aiming to optimize the clinical performance of the cement in different scenarios [39].

While zinc phosphate cement continues to be widely used in dentistry, advancements in material science have led to the development of alternative cement types with enhanced properties. The choice of cement depends on various factors, including the specific clinical application, desired bonding strength, and esthetic requirements. However, zinc phosphate cement exhibits relatively low tensile strength. Additionally, it has a high solubility, particularly in acidic environments, making it unsuitable in cases where there is a risk of pulpal irritation [26]. Moreover, due to its poor flexural strength, this cement is not recommended for bonding ceramic and composite crowns [13, 37]. The composition of zinc phosphate cement typically includes zinc oxide powder, magnesium oxide powder (3-10%), phosphoric acid, water, and buffers [14]. This type of cement has been commonly used for bonding metal, porcelain, and metal-ceramic indirect restorations, as well as for inlays, crowns, bridges, posts, orthodontic bands, and cavity liners in crowns and bridges, owing to its satisfactory mechanical retention properties [27].

However, the use of zinc phosphate cement as a temporary dental cement has certain disadvantages compared to resin-based cements. These include higher solubility, lower compressive and flexural strength, increased microleakage, dental pulp irritation, and reduced bond strength. Consequently, its utilization has become limited [16]. The cementation process of zinc phosphate cements is rapid and highly exothermic, necessitating careful control of the reactions and dissipation of the heat generated by mixing the precursors in a cool and dry container. After the setting reaction is complete, any excess and unreacted phosphoric acid can dissolve the smear layer and penetrate the dentinal tubules, potentially leading to pulpal irritation. The pH of the cement varies from 2.14 immediately after mixing to 5.5 after 24 hours, which may contribute to post-operative discomfort [17, 32, 35]. Recent studies have focused on improving the properties of zinc phosphate cement through modifications to its composition and the incorporation of additives to enhance its mechanical and physical characteristics. For example, the addition of nanoparticles and fibers has shown promise in increasing the strength and reducing the solubility of the cement. Furthermore, surface treatments and adhesive systems have been explored to enhance the bond strength between zinc phosphate cement and various restorative materials.

It is important for dental professionals to consider the specific clinical requirements and limitations of zinc phosphate cement when selecting the most suitable cement for a given case. Advances in cement technology continue to offer alternatives with improved properties, such as resin-based cements, which provide enhanced bonding strength and better aesthetics[35, 18].

Zinc Oxide-Eugenol (ZOE) and Noneugenol Cements

Zinc oxide-eugenol (ZOE) is a widely used water-based temporary dental cement composed of reactive zinc oxide, eugenol (4-allyl-2-methoxyphenol, a component of oil of cloves), and accelerators such as acetic acid, zinc acetate, zinc alkanoates, zinc propionate, and 2-ethoxybenzoic acid (EBA). The setting reaction of ZOE cement is based on the hydrolysis reaction between eugenol (which provides hydrogen ions) and zinc oxide, resulting in the formation of a zinc eugenolate gel ($Zn(C_{10}H_{11}O_2)_2$), as depicted in Figure 1 [3, 19, 34].

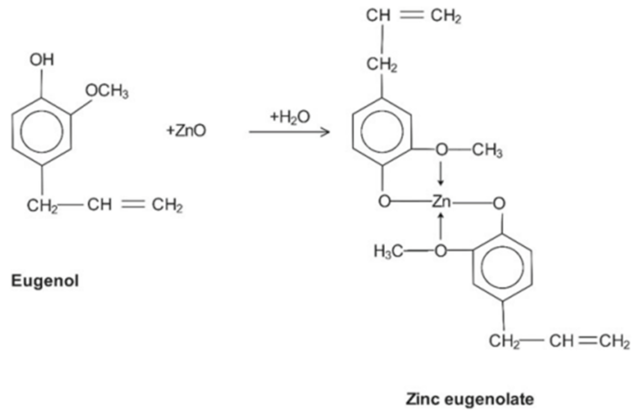

Fig 1. The hydrolysis reaction between eugenol (hydrogen ion provider) and zinc oxide is the basis of the setting reaction.

ZOE cement is favored in dental applications due to its antibacterial properties and ease of manipulation. It exhibits moisture sensitivity, allowing for rapid setting in the oral environment while providing an extended working time of 4-14 minutes at room temperature. However, the compressive strength of ZOE cement ranges from 13 MPa to 38 MPa, making it suitable for use as liners and provisional cements. ZOE cements are known to undergo setting shrinkage, with values of 0.86% and 0.32% for dry and wet conditions, respectively. Despite exhibiting relatively high thermal expansion and shrinkage during the setting process, ZOE cements demonstrate plastic behavior, which makes them suitable for sealing applications and helps minimize pulp inflammation. Furthermore, ZOE cements have a neutral pH and offer greater biocompatibility compared to resin-modified glass ionomers and resin cements [20].

In recent years, efforts have been made to improve the properties of ZOE cement and overcome some of its limitations. Researchers have explored modifications to the cement formulation by incorporating additives such as antimicrobial agents, reinforcing fillers, and resin components to enhance its mechanical strength, antimicrobial efficacy, and adhesion to tooth structure. Additionally, investigations into the effect of various accelerators and setting modifiers on the properties of ZOE cement have been conducted.

While ZOE cement remains a popular choice for temporary restorations and as a liner, its use as a definitive cement has decreased with the emergence of resin-based cements, which offer superior mechanical properties and adhesive capabilities. The selection of a cement depends on the specific clinical requirements, including the duration of use, desired strength, and need for adhesion. Dental professionals should consider the advantages and limitations of different cement types to make informed decisions for successful clinical outcomes [21].

On the other hand, eugenol is released from the hydrolysis of the salt matrix in ZOE cements and possesses pain-relieving properties. However, when ZOE cements come into contact with water or saliva, the breakdown of zinc eugenolate occurs, leading to the release of zinc hydroxide and eugenol, which can cause inflammation in the dental pulp. Despite this, zinc oxide-eugenol cement plays a significant role in various dental applications, including root canal sealing, periodontal coating, cavity base, inelastic impression material, and temporary restorations such as crown cementing and fillings [23].

In the mid-1970s, modifications were made to ZOE cements by introducing reinforced formulations and incorporating orthoethoxybenzoic acid (EBA), resulting in improved mechanical properties. These modified cements can be utilized as definitive cements. In contrast to traditional ZOE cements, eugenol-free or noneugenol (NE) cements are stronger and more hydrolytically stable, making them suitable for long-term provisional restorations. These NE cements offer convenient retention and possess longer working and setting times [24, 31, 34]. Table 2 provides an overview of some properties of zinc oxide-eugenol cements.

Table 2. Properties of Zinc Oxide-Eugenol Cements

Property	Description
Composition	Zinc oxide powder, Eugenol liquid
Setting Reaction	Chemical setting reaction
Working Time	1-2 minutes
Setting Time	10-15 minutes
Strength	Relatively low strength
Solubility	Slightly soluble in oral fluids
Thermal Insulation	Excellent thermal insulation
Sedative Effect	Provides a sedative effect on the pulp
Biocompatibility	Generally biocompatible
Adhesion	Limited adhesive properties
Pulp Irritation	Potential for pulp irritation, especially with prolonged use
Usage	Temporary cementation, pulp capping
Fluoride Release	Minimal to no fluoride release
Aromatic Flavor	Eugenol can provide a distinct aromatic flavor

Continued research aims to further enhance the properties of ZOE cements, particularly in terms of their mechanical strength, biocompatibility, and antimicrobial efficacy. Investigations into alternative materials and additives have been conducted to improve the stability and performance of ZOE-based cements [46, 26].

While ZOE cements have been widely used in dentistry, it is essential to consider their limitations and potential adverse effects, such as pulp inflammation, when selecting the most appropriate cement for a specific clinical situation. Dental professionals should carefully evaluate the requirements of each case and consider alternative cement options, such as resin-based cements, which offer superior mechanical properties, reduced solubility, and improved esthetics [28].

Zinc Polycarboxylate Cements

Zinc polyacrylate cements, also known as polycarboxylate cements, belong to the group of polyelectrolyte cements and were introduced by Smith in 1968. These cements were the first to exhibit chemical adhesion properties, allowing them to form bonds with the calcium ions present in the tooth structure. The intention behind the development of this type of cement was to combine the favorable mechanical properties of zinc phosphate cements with the biocompatibility and bonding capabilities of zinc oxide-eugenol (ZOE) cements [29].

Zinc polycarboxylate cements set through an acid-base reaction between a powder consisting of zinc oxide, magnesium oxide, aluminum oxide, and bismuth, and polyacrylic acid. The formation of chemical bonds during the application of these water-based cements helps prevent microleakage of microorganisms, resulting in their biocompatibility and reduced irritation to the dental pulp when compared to zinc phosphate cements.

Despite these advantages, zinc polycarboxylate cements have certain limitations that have restricted their usage. They are highly soluble, which compromises their long-term stability. The mechanical properties of these cements are often inadequate, making them less suitable for permanent applications. Additionally, their manipulation can be challenging, and their esthetics tend to be opaque, making them more suitable for temporary use rather than as a permanent cement [30, 47].

Efforts have been made to address these limitations and improve the properties of zinc polycarboxylate cements. Modifications to the cement composition and the addition of reinforcements, such as glass fibers or fillers, have been explored to enhance their mechanical strength and durability. Researchers have also investigated the incorporation of nanoparticles and antimicrobial agents to improve the solubility and antimicrobial properties of these cements.

Dental professionals must consider the specific clinical requirements and limitations of zinc polycarboxylate cements when choosing the appropriate cement for a given case. Alternative cement options, such as resin-based cements, offer improved mechanical properties, reduced solubility, and enhanced esthetics, providing clinicians with a broader range of choices for long-term restorations[31].

CONCLUSIONS

1. Zinc-based dental cements have found applications in various clinical scenarios, including cementation of metal, porcelain, and metal-ceramic restorations, cavity liners, provisional restorations, root canal sealers, and periodontal dressings. Their use as temporary cements has been particularly beneficial due to their ease of removal and ability to provide short-term stability.

2. Future research directions include the development of bioactive and antimicrobial zinc-based cements, as well as the exploration of nanotechnology-based approaches for improved properties. Moreover, the integration of zinc-based cements with adhesive systems and the investigation of their performance in combination with different restorative materials hold promise for further advancements in this field.

3. Zinc-based dental cements have a significant role in restorative dentistry, offering a range of properties and applications. Although they have limitations, ongoing research and advancements aim to improve their performance and expand their clinical utility. With further developments, zinc-based cements may continue to play a crucial role in dental restorations, providing clinicians with reliable and versatile options for different clinical scenarios.

REFERENCES

1. Anusavice, K. J., Shen, C., & Rawls, H. R. (Eds.). (2012). Phillips' science of dental materials. Elsevier Health Sciences.
2. Höland, W., Schweiger, M., Rheinberger, V. M., & Kappert, H. (2009). Bioceramics and their application for dental restoration. Advances in Applied Ceramics, 108(6), 373–380.
3. Powers, J. M., Sakaguchi, R. L., & Craig, R. G. (2012). Craig's restorative dental materials/edited by Ronald L. Sakaguchi, John M. Powers. Philadelphia, PA: Elsevier/Mosby.
4. Bergmann, C. P., & Stumpf, A. (2013). Dental ceramics microstructure, properties and degradation, topics in mining, Metallurgy and Materials Engineering. Berlin, Heidelberg: Springer.
5. Zhang, Y., & Kelly, J. R. (2017). Dental ceramics for restoration and metal veneering. Dental Clinics of North America, 61(4), 797–819.
6. Zanelli, C., Raimondo, M., Guarini, G., & Dondi, M. (2011). The vitreous phase of porcelain stoneware: composition, evolution during sintering and physical properties. Journal of Non Crystalline Solids, 357(16–17), 3251–3260.
7. Saint-Jean, S. J. (2014). Dental glasses and glass-ceramics. In Advanced Ceramics for Dentistry, 255–277
8. Ho, G. W., & Matinlinna, J. P. (2011). Insights on ceramics as dental materials. Part I: ceramic material types in dentistry. Silicon, 3(3), 109–115.
9. McLaren, E. A., & Cao, P. T. (2009). Ceramics in dentistry—part I: classes of materials. Inside dentistry, 5(9), 94–103.
10. Kelly, J. R. (2008). Dental ceramics: What is this stuff anyway? The Journal of the American Dental Association, 139, S4–S7.
11. Shenoy, A., & Shenoy, N. (2010). Dental ceramics: An update. Journal of conservative dentistry: JCD, 13(4), 195.
12. Denry, I., & Holloway, J. (2010). Ceramics for dental applications: a review. Materials, 3(1), 351–368.
13. Pollington, S., & van Noort, R. (2009). An update of ceramics in dentistry. Int J Clin Dent, 2(4), 283–307.
14. Höland, W., Schweiger, M., Watzke, R., Peschke, A., & Kappert, H. (2008). Ceramics as biomaterials for dental restoration. Expert Review of Medical Devices, 5(6), 729–745.
15. Conrad, H. J., Seong, W. J., & Pesun, I. J. (2007). Current ceramic materials and systems with clinical recommendations: a systematic review. The Journal of prosthetic dentistry, 98(5), 389–404.
16. Kelly, J. R., & Benetti, P. (2011). Ceramic materials in dentistry: historical evolution and current practice. Australian Dental Journal, 56, 84–96.
17. Silva, L. H. D., Miranda, R. B. D. P., Favero, S. S., Lohbauer, U., & Cesar, P. F. (2017). Dental ceramics: A review of new materials and processing methods. Brazilian oral research, 31.
18. Höland, W., Rheinberger, V., Apel, E., van't Hoen, C., Höland, M., Dommann, A. & Graf Hausner, U. (2006). Clinical applications of glass-ceramics in dentistry. Journal of Materials Science: Materials in Medicine, 17(11), 1037–1042.
19. Denry, I., & Kelly, J. R. (2014). Emerging ceramic-based materials for dentistry. Journal of Dental Research, 93(12), 1235–1242.
20. de Carvalho Ramos, N., Campos, T. M. B., de La Paz, I. S., Machado, J. P. B., Bottino, M. A., Cesar, P. F., et al. (2016). Microstructure characterization and SCG of newly engineered dental ceramics. Dental Materials, 32(7), 870–878.
21. Raigrodski, A. J. (2004). Contemporary materials and technologies for all-ceramic fixed partial dentures: a review of the literature. The Journal of Prosthetic Dentistry, 92(6), 557–562.
22. Denry, I., & Kelly, J. R. (2008). State of the art of zirconia for dental applications. Dental Materials, 24(3), 299–307.
23. Turon-Vinas, M., & Anglada, M. (2018). Strength and fracture toughness of zirconia dental ceramics. Dental Materials, 34(3), 365–375.
24. Piconi, C., Condo, S. G., & Kosmaˇc, T. (2014). Alumina-and zirconia-based ceramics for load-

bearing applications. In Advanced ceramics for dentistry 219–253.
25. Yin, L., Song, X. F., Song, Y. L., Huang, T., & Li, J. (2006). An overview of in vitro abrasive finishing & CAD/CAM of bioceramics in restorative dentistry. International Journal of Machine Tools and Manufacture, 46(9), 1013–1026.
26. Hill, E. E. (2007). Dental cements for definitive luting: a review and practical clinical considerations. Dental Clinics of North America, 51(3), 643–658.
27. Wilson, A. D., & Nicholson, J. W. (2005). Acid-base cements: their biomedical and industrial applications. Cambridge University Press.
28. Sunico-Segarra, M., & Segarra, A. (2015). A practical clinical guide to resin cements. Berlin Heidelberg: Springer.
29. Albers, H. F. (2002). Tooth-colored restoratives: principles and techniques. PMPH-USA. Dental Restorative Materials
30. Kumar, M., & Kumari, S. (2016). Resin-modified Glass Ionomer Cements and its Use in Orthodontics-Concept Old is Gold: View Point. International Journal of Dental and Medical Speciality, 3(3), 10.
31. Wingo, K. (2018). A review of dental cements. Journal of veterinary dentistry, 35(1), 18–27.
32. McCabe, J. F., & Walls, A. W. (Eds.). (2013). Applied dental materials. Wiley.
33. Powers, J. M., & Wataha, J. C. (2015). Dental Materials-E-Book: Foundations and Applications. Elsevier Health Sciences.
34. Von Fraunhofer, J. A. (2013). Dental materials at a glance. Wiley.
35. Shelton, R. (Ed.). (2016). Biocompatibility of Dental Biomaterials. Woodhead Publishing.
36. Tabatabaian, F. (2019). Color aspect of monolithic zirconia restorations: A review of the literature. Journal of Prosthodontics, 28(3), 276–287.
37. de la Macorra, J. C., & Pradíes, G. (2002). Conventional and adhesive luting cements. Clinical Oral Investigations, 6(4), 198–204.
38. Lad, P. P., Kamath, M., Tarale, K., & Kusugal, P. B. (2014). Practical clinical considerations of luting cements: A review. Journal of international oral health: JIOH, 6(1), 116.
39. Wilson, A. D., Paddon, J. M., & Crisp, S. (1979). The hydration of dental cements. Journal of Dental Research, 58(3), 1065–1071.
40. Moshaverinia, A., Roohpour, N., Chee, W. W., & Schricker, S. R. (2011). A review of powder modifications in conventional glass-ionomer dental cements. Journal of Materials Chemistry, 21(5), 1319–1328.
41. Sidhu, S. K., & Nicholson, J. W. (2016). A review of glass-ionomer cements for clinical dentistry. Journal of functional biomaterials, 7(3), 16.
42. Mount, G. J. (2001). An atlas of glass-ionomer cements: a clinician's guide. CRC Press.
43. Deb, S., & Chana, S. (2015). Biomaterials in relation to dentistry. In Biomaterials for Oral and Craniomaxillofacial Applications (Vol. 17, pp. 1–12). Karger Publishers.
44. Sidhu, S. K. (2011). Glass-ionomer cements restorative materials: a sticky subject? Australian Dental Journal, 56, 23–30.
45. Hafshejani, T. M., Zamanian, A., Venugopal, J. R., Rezvani, Z., Sefat, F., Saeb, M. R., & Mozafari, M. (2017). Antibacterial glass-ionomer cements restorative materials: A critical review on the current status of extended release formulations. Journal of Controlled Release, 262, 317–328.
46. Noumbissi, S., Scarano, A., & Gupta, S. (2019). A literature review study on atomic ions dissolution of titanium and its alloys in implant dentistry. Materials, 12(3), 368.
47. Roberts, H. W., Berzins, D. W., Moore, B. K., & Charlton, D. G. (2009). Metal-ceramic alloys in dentistry: A review. Journal of Prosthodontics: Implant, Esthetic and Reconstructive Dentistry, 18(2), 188–194.