A review of tribological properties of dental materials: evaluation of the important influential factors using a pin-on-disk tribometer

Abstract: There is a wide range of dental restorative composite materials available in the market, however selection of a good wear resistant material is challenging. The durability of different dental materials in the mouth depends strongly on their tribological characteristics. However, clinical efficacy of these restorative materials cannot be predicted only based on their tribological characteristics. Nevertheless, these characteristics can support the investigation of the consequences of modifications to the composition. Numerous laboratory studies have been used to examine the different tribological properties for a while, which can help the clinicians in selecting the appropriate dental materials. This paper reviews the important influential factors while evaluating tribological properties of the dental composite materials using a pin-on-disc tribometer, which are surface roughness of specimen, normal load, type of pin material, pH level, loading cycle and abrasive medium. The influences of the factors on measurements of tribological characteristics and the selection of restorative materials are also discussed.

Keywords: Dental composite, pin-on-disc tribometer, abrasive medium, loading cycle, pH level, surface roughness.

1 Introduction

Dental composite materials made of resin are frequently used in dentistry to create restorations that directly resemble natural teeth. These materials are also known as dental composite, dental composite resin, dental resin composite, and dental polymer composite in the literature [B2]. According to a study by Eltahlah et al.(2018), Glass ionomers/resin-modified glass ionomers/dental composites (13.4%), amalgams (40.9%), resin-based dental composites (44%), and other types of restoration (e.g., indirect and temporary restorations) (1.7%) have been used as dental restorative materials since 1981. In dentistry, utilizing resin-based dental composites rather than amalgam is becoming more popular. Additionally, repair of restorations placed prior to the year 2000 accounted for 56% of all dental restorations, rising to 58% for restoration implantation completed after the year 2000. These figures demonstrate the short lifespan of dental restorations and the elevated cost of dental care due to the subsequent clinical treatments [B1].

Wear is still a significant issue despite improvements in the mechanical qualities of composite resins, especially in patients who exhibit parafunctional behaviors like bruxism [A1]. According to estimates, 800 million composite resin restorations were applied worldwide in 2015 alone, with 80% of those restorations being placed on posterior teeth [A2]. According to same study, it was also revealed that 5% of posterior restorations failed due to fracture and 12% showed significant wear over a period of 10 years. In the next ten years, almost 32 million composite resin restorations that were put in place in 2015 may need to be fixed or replaced owing to fracture. Approximately 77 million composite resin restorations on posterior teeth around the world were expected to show considerable wear [A3].

Resin composites exhibit a definite pattern of wear since the wear resistance is affected by the characteristics associated with their composition. In composites, filler particles are distributed within a brittle polymer. The fillers are typically referred to as pre-polymer fillers and are made from glass particles like silicon oxide (quartz), barium aluminum silicate, or fillers that

are generated from the matrix polymer by grinding the matrix to smaller particles. The polymers are made from a variety of monomers, including triethyleneglycol dimethacrylate (TEGDMA), urethane dimethacrylate (UDMA), and bisphenol-A-glycidyl methacrylate (Bis-GMA). They are polymerized using visible light-sensitive initiators [C1]. The filler particles should entirely receive the loading force that is applied to the matrix.

The wear characteristics are influenced by (i) the quantity, shape, size and hardness of filler particles, (ii) bonding quality of filler and polymer matrix and (iii) the 3-D polymerization dynamics of the polymer [C2]. Composition of the ingredients in the material also influences the physical properties such as elasticity modulus, fracture toughness, flexural strength, Vickers hardness, curing depth, etc [C1]. These physical properties also affect the wear of composites. Wear rate of composites is also dependent on the friction coefficient and the surface roughness [C3].

Wear in the oral cavity is a complex phenomenon influenced by a number of variables. Wear in the oral cavity may be due to only one or a combinations of mechanisms (adhesive, abrasive, corrosive, fatigue, etc)[1]. In essence, this explains why simulation of wear of dental materials is so difficult. Despite the significant advancements in dental materials over the past few decades, wear of restorative materials remains a significant issue, particularly when dealing with composite resins.

Literature shows there is no standardized testing protocols for dental materials to ensure consistency and comparability of results. There might be variations in test parameters across different studies, such as the choice of counterface material, sliding speed, and applied load [D2]. The temperature in the oral cavity can vary due to hot or cold food and beverages, affecting the tribological behavior of dental materials. There is a limited study on the impact of environmental factors (e.g., temperature, humidity) on the tribological properties of dental materials, which could affect their performance in real-world applications [D4]. Many studies do not fully replicate the complex and dynamic oral environment in which dental materials are subjected to wear and friction. The gap lies in the need for improved experimental designs that better mimic the oral conditions, considering factors such as varying loads, angles of contact, and the presence of saliva [D4]. There are limited research investigating the influence of surface roughness and how different polishing or finishing techniques impact the wear and friction properties of dental materials [D1]. The understanding of wear mechanisms and surface analysis in dental materials tested still be limited, warranting further investigation. The use of lubricants or oral fluids in the oral cavity can significantly affect the tribological properties of dental materials. However, there might be a lack of comprehensive studies investigating the impact of different lubricants and their concentrations on the wear and friction behavior of dental materials [D3, D4].

The structure and composition of composite resins directly influence and limit their wear resistance in a number of ways. Dental professionals understand the importance of lab and clinical studies before implementing the materials in practise. In these situations, selecting the right material with the expectation of prolonged performance requires a good understanding of

its tribological and mechanical qualities[2,3]. Pin-on-disc tribometer is the most widely used test equipment for calculating friction and wear of different materials under different conditions. The test results using this setup are very much influenced by many factors such as normal load, loading cycle, abrasive medium, pH level, surface roughness of specimen, etc. Researchers conduct the tests of wear or friction in the pin-on-disc setup based on these factors. This paper presents a review of studies conducted using pin-on-disc tribometer considering different variables affecting the wear or friction.

2 Influencing factors on Tribological Properties

2.1 Effect of surface roughness

Surface roughness can have a significant effect on the tribological properties of dental materials when using a pin-on-disk tribometer. Tribological properties refer to the study of friction, wear, and lubrication of interacting surfaces in relative motion. When evaluating the tribological properties of dental materials, the surface roughness of the materials can influence the coefficient of friction, wear rate, and surface damage. A rough surface can lead to increased friction and wear due to increased contact area and localized stresses, which can cause surface damage. Conversely, a smooth surface can reduce friction and wear, as well as reduce the surface damage.

One of the essential mechanical characteristics of restorative material is surface roughness. It indicates that the procedure used for polishing or surface finishing has an impact on how rough the surface of resin composites is[4]. After a year of water storage, the surface roughness composite resins and solubility characteristics remained unaltered[5]. Additionally, quick polishing had no effect on the surface abrasiveness, micro-hardness, or micro-leakage of composite resin based on silorane[6]. Aluminum oxide discs and water were proven to be an efficient way for polishing the materials. Water not only removes heat but also deteriorated particles from the surface of the restoration, which need to be removed right away. Based on the fluctuation in speckle statistics of light scattered from the measured surface, a straightforward, sensitive, and reliable method is introduced for measuring the roughness of dental Zirconia[7]. The antagonist material has an impact on the two-body wear resistance of modern composite dental materials. According to one study, utilising a harder structure of an antagonist composite material should be avoided or, if it is a hard fill, the particles should be made smaller to prevent volume loss based on contact-wear mechanism[8].

Sripetchdanond and Leevailoj (2014) measured the surface roughness of enamel specimens worn by monolithic zirconia, composite resin group, glass ceramic, and enamel material after performing the wear test. Monolithic zirconia, glass ceramic, and enamel material showed the significant change in surface roughness after the wear test but in case of composite resin, there is no remarkable difference in surface roughness after the wear test[9]. According to Jang et al. (2019), the surface roughness of the sand-blasted polished specimens showed negligible variations throughout the wear test, regardless of the original state of roughness[10]. The results of the study conducted by Ghazal and Kern (2009) stated that human enamel attrition was considerably influenced by the surface roughness of ceramic material[11]. According to Preis et al. (2015), the change in roughness of polished and ground zirconia was hardly affected by the wear process[12]. Since zirconia is used in clinics, it must be well-polished to retain a high level of wear resistance[11].

Kazi (2020) investigated the influence of roughness on wear enamels. Two zirconia surface finishes were investigated as part of wear validation tests for a dental wear simulator[13]. The wear characteristics of two enamel surfaces having surface roughness values R_a = 0.72 μm and R_a = 0.11 μm have were studied. The results showed that the two varying roughness values did not result in any noticeable enamel wear. This can be explained by the hypothesis proposed by Lawson et al (2014) that surface roughness Ra ≥ 1.5 caused by the bur used for therapeutic adjustments would considerably accelerate antagonist enamel attrition[14]. In an investigation, Mitov et al. (2012) found that zirconia roughened with a fine 30 μm diamond bur (Ra= 1.18 μm) generated no noticeable variation in enamel wear compared to polished zirconia but exhibited less enamel wear than zirconia roughened with a coarse 100 μm diamond bur (R_a= 3.95 μm)[15]. Similarly, no difference in opposing enamel wear was detected between smooth (R_a = 0.12 μm) and rough (R_a = 0.44 μm) zirconia surfaces[16], rough (R_a = 0.75 μm) and smooth (R_a = 0.24 μm) zirconia surfaces[11], and between repolished (R_a = 1.11 μm) and adjusted (R_a =2.73 μm) zirconia surfaces[14].

Turssi et al. (2005) showed that surface roughness had no effect on the abrasive wear of nano- and micro-filled composites[17]. They concluded that surface irregularities had little influence on three-body abrasion. However, they noted that the timeframe of their experiments may have been the likely cause of disguising the impact of polishing on wear. According to Ratanapridakul et al. (1989), polished materials exhibit more wear than the unpolished materials[18]. They concluded that rotary polishing equipment causes scratches on the material surface, lowering abrasion resistance. Kumar et al (2020) assessed the surface roughness of two distinct restorative materials i.e. zirconia and cobalt chromium over the human enamel[19]. The R_a value for monolithic zirconia was lower than that for cobalt chromium specimen. The smaller grain size increases the energy required to separate the grain from the ceramic matrix, making the material significantly more wear resistant. This explains why the surface roughness of the monolithic zirconia samples studied did not alter with the wear of opposing enamel.

Di Fiore et al. (2022) discussed the potential impact of tooth brushing on the surface roughness of CAD/CAM materials containing resin and concluded that artificial teeth brushing had an impact on the surface roughness of the majority of these materials[20]. Table 1 contains data collected by Di Fiore et al. (2022) which correlate the tooth brushing and surface roughness.

Table 1. Correlation between tooth brushing and surface roughness.

Author	**Sample**	**Correlation between tooth brushing and surface roughness**
Mormann et al.,[21]	Lava Ultimate (3M ESPE) Vita Enamic (Vita Zahnfabrik)	No
Koizumi et al.,[22]	Vita Enamic (Vita Zahnfabrik) Gradia Block (GC) Shofu Block Hc (Shofu) Lava Ultimate (3M ESPE)	YES (Cerasmart and Shofu Block) NO (other materials)

	Katana Avencia (KurarayNoritake) Cerasmart (GC)	
Flury et al.,[23]	Paradigm MZ100 (3M ESPE) Lava Ultimate (3M ESPE) Vita Enamic (Vita Zahnfabrik) Ambarino High Class(Creamed)	YES (Ambarino) NO (Lava Ultimate and Vita Enamic)
Kamonkhantikul et al.,[24]	Shofu Block Hc (Shofu) Cerasmart (GC) Gradia Block (GC) Hybrid Resin Block (Yamamoto) Lava Ultimate (3M ESPE) Vita Enamic (Vita Zahnfabrik)	YES
de Andrade et al., [25]	Cerasmart (GC) Vita Enamic (Vita Zahnfabrik) Lava Ultimate (3M ESPE)	YES
Nima et al., [26]	Vita Enamic (Vita Zahnfabrik) Lava Ultimate (3M ESPE)	YES

In order to minimize the effect of surface roughness on tribological properties, it is important to standardize the surface roughness of the specimens being tested. This can be achieved by controlling the surface finish of the samples prior to testing or by using a standard polishing technique to achieve a consistent surface finish across all samples. Additionally, it is important to consider the impact of surface roughness on the test results and to interpret the data accordingly. For example, if the surface roughness of the samples varies significantly, the data may need to be analyzed in a way that accounts for this variability, such as through statistical analysis. In summary, surface roughness can have a significant impact on the tribological properties of dental materials when using a pin-on-disk tribometer. Standardizing the surface finish of the samples and carefully interpreting the test results can help mitigate the effect of surface roughness on the data obtained from the testing.

2.2 Loading force

The applied loading condition is another important parameter that affects the tribological properties of dental materials evaluated using the pin-on-disk tribometer. The loading condition refers to the manner in which the load is applied on the sample, and it includes the type of loading (e.g., static or dynamic) and the loading rate (e.g., constant or variable). The loading condition can affect the friction and wear properties of dental materials in various ways. For instance, a higher loading rate can lead to higher friction and wear rates due to the increased temperature generated by the frictional heat. Similarly, dynamic loading conditions can produce different wear mechanisms compared to static loading conditions, which can result in different tribological properties.

At various applied loads, the correlation between the weight percentage and the length of glass fibers added into a resin component and the wear resistance characteristics of these materials is investigated by Callaghan *et al.* [27]. Investigations are also carried out on how these load characteristics affect the friction coefficient. By increasing the normal load applied to the top of the arm from 4.45 N to 22.24 N, the coefficient of friction was found to be decreasing. It

was demonstrated that the enamel wear caused by 78N load was two times of that caused by 20N load[28]. Furthermore, enamel and composite wear increase with the increase in the load[11]. The coefficient of friction is also influenced by occlusal load and geometric characteristics such as abrasive surface texture and contact area. Higher loads produce larger friction coefficients, which increases wear[29]. However, when the load increases, the bonding between the matrix and filler becomes more prone to deterioration, and therefore the wear increases[30].

The influence of applied normal load on the tribo-corrosion behavior of the test specimens, Ti-10Zr Alloy and Porous TiO_2-ZrO_2 was investigated[31]. The sliding tests were performed with two normal loads of 2 N and 5N. Under constant rotational speed and a fixed number of sliding cycles, the frictional coefficient decreases with increase in normal load. The linear reciprocating (pin-on-plate) and ball crater (ball-on-plate) wear tests were employed to explore the wear mechanisms of composite resins[32]. The specimens in both apparatuses were subjected to loads ranging from 0.1 to 1 kg. Two-body wear for dental composites was tested using dry sliding at varying normal loads (20, 40, and 60 N)[33]. According to the results of the ANOVA analysis, the volumetric wear was significantly influenced by filler content and normal load, both of which had a significant level of 5%.

A pin-on-disk tribometer was used with contact loads that varied from 1 to 20 N to investigate the two-body wear mechanisms of composites. SEM analysis was used to examine the wear tracks[34]. Examining the worn surfaces revealed that regardless of the load, a thin layer was observed on the wear track. When subjected to higher loads, the film became discontinuous and partially removed however at low loads the worn track was almost entirely covered. Film separation at the higher loads was the cause of the increase in wear volume. In a different study, at low loads, wear predominantly occurs by a tribochemical mechanism, which involves the generation and dissolution of reaction products[35]. At higher loads, wear is caused by a mix of tribochemical reactions and mechanical separation of the surface film[36]. Table 2 represents a range of loading conditions under which different dental materials were tested.

Table 2. A range of loading conditions used by different researchers.

Author	Materials	Equipment	Loading conditions
Barange and Hambire [36]	3M Filtek Z250, 3M Filtek Z350	Pin-on-disc tribometer (Two-body wear tester).	29.43N, 39.24N, and 49.05N
Marquis et al., [37]	3M Z100, 3M P50	Pin-on-disc tribometer (Two-body wear tester).	3N, 6N, 9N, 12N, and 15N
Tabatabaei et al., [38]	3M Filtek P60, 3M Filtek P90	Pin-on-disc tribometer	70N and 150N
Arsecularatne et al., [39]	DC1containing 61% vol. of Alumino silicate glass, DC2 containing 61% vol. of Strontium glass, DC3 containing 51% wt.	Reciprocating pin-on-disc tribometer	2N, 5N, and 10N

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Dawood J. [40]	Polyester, polyester reinforced with glass fiber, polyester reinforced with Kevlar fiber	Pin-on-disc tribometer	2N, 4N, 6N, and 8N
Dziedzic, et al [41]	CeramX mono and I-Light.	Ball-on-disc tribotester	10N and 20N
Badran et al [42]	PMMA nanocomposites	Reciprocating Pin-on-disk tribometer	2N, 4N, 6N, 8N and 10N
Prasertwong, et al [43]	GC, GCF, GCC, GCCF	Pin-on-disc tribometer	10N

It is also important to note that the loading force should not exceed the maximum load capacity of the tribometer, as this can lead to equipment failure and inaccurate results. It is, therefore, recommended to consult the equipment manual or the manufacturer for the maximum load capacity of the tribometer. In addition, the loading condition can also affect the repeatability and reproducibility of the results obtained from the pin-on-disk tribometer. For example, the use of different loading rates or loading modes can lead to different surface topographies, which can affect the friction and wear behavior of the materials.

Therefore, it is important to carefully consider the loading condition when evaluating the tribological properties of dental materials using the pin-on-disk tribometer. It is recommended to choose a loading condition that mimics the real-world conditions as closely as possible, while also ensuring that the results obtained are repeatable and reproducible[44, 45, 46]. In summary, the applied loading condition is an important parameter that can affect the tribological properties of dental materials evaluated using the pin-on-disk tribometer. It is important to carefully consider the loading condition to ensure accurate and representative results that can be reproduced under different test conditions.

2.3 Lubricant or pH level

The use of lubrication and the pH level of the surrounding environment are two additional factors that can affect the tribological properties of dental materials when evaluated using a pin-on-disk tribometer. Lubrication is used to reduce friction and wear in a variety of tribological applications, and it is commonly used in dental applications to reduce the wear of restorative materials, such as composites and ceramics. The use of lubrication can significantly affect the friction and wear properties of dental materials, and the choice of lubricant can also impact the test results[47,48,49]. The lubricant must be compatible with the dental material being tested and should mimic the oral environment as closely as possible. The pH level of the surrounding environment can also affect the tribological properties of dental materials. The oral environment is dynamic, and changes in pH can affect the surface chemistry and morphology of the materials. For example, acidic environments can dissolve the mineral content of tooth enamel and demineralize restorative materials, while basic environments can corrode metals and increase wear rates.

A pin-on-disc wear device was used to study the effects of water on two-body wear rate of various dental composite materials[50]. In comparison to micro-hybrid resins, nanohybrid resins demonstrated much reduced abrasive wear, whether used directly or indirectly. In both the water exposure and control groups, Tetric N-Ceram, Herculite Classic, and GrandioSO were found to have lower wear rates than the direct resin composites and indirect resin composites. The in vitro wear loss of human enamel specimens was investigated in a reciprocating wear test[51]. The test was performed under a cyclic load of 5 N with lubricants including citric acid (at pH 3.2 and 5.5), acetic acid (at pH 3.2 and 5.5) and distilled water. The corrosion potential of a utilised lubricant might be connected to the substance loss of enamel during wear. When using a lubricant with very low corrosion potential, like distilled water, delamination dominated the wear process and resulted in significant wear loss. In contrast, the wear process altered in an environment with medium corrosion potential, such as citric acid at pH 3.2 and 5.5 and acetic acid at pH 5.5, to shaving of the softened layer with minimal material loss.

The wear of three dental resin composites were examined using artificial saliva at pH 7 (neutral)[39]. An antagonist of the enamel cusp that articulated against a flat dental resin composite surface in a controlled liquid medium was used in the investigation. They also compared the findings of Wu et al. [51] on enamel wear. Since artificial saliva was not utilised in the testing, enamel-on-enamel wear cannot be meaningfully compared. Throughout the duration of the experiment, the presence or absence of lubricants will cause a dental composite to wear at rates comparable to those observed with deionized water, synthetic saliva, and natural human saliva as lubricants[52]. Following the completion of each frequency cycle, wear depth was assessed. The original findings demonstrated that the simulation with no lubrication caused the most wear during the test durations. When artificial saliva and human saliva were interposed, deionized water caused more wear than the latter, and both types of saliva created a comparable amount of wear. The findings revealed that the choice of lubricating medium had an impact on how quickly dental materials wore down in the lab.

The wear characteristics of two different dental materials (Super Lux and VHL hybrid) were evaluated using a pin-on-disc tribometer[53]. Experiments were performed both in dry and wet (water as lubricant) mode. For both the modes, wear increased with time. Out of acidic, neutral and basic medium, the wear was maximum in the acidic medium and the minimum in the basic medium. How erosive pH cycling affected the wear of several restorative materials (resin-modified glass-ionomer and resin composites) was assessed[54]. The specimens were kept in artificial saliva during the entire experiment after being submerged in cola drink for 5 minutes. No appreciable variations in wear were detected.

It was explored whether the combination of citric acid and a rough surface will cause significant wear behaviour in a resin composite[55]. Reciprocating ball-on-flat wear tests were conducted in both citric acid (pH = 5.5) and distilled water, respectively. In an acidic media, all specimens showed mild wear behaviour with low COF and reduced surface abrasion. Citric acid lubrication can sustain mild wear behaviour regardless of the initial surface roughness, reducing the negative impacts of excessive roughness. The effects of marble and nano alumina were investigated on the how dental composites wear[56]. Under the influence of artificial saliva, a two-body abrasive wear test was conducted on the dental wear simulator. Compared to the marble dust-filled dental composites, the nano-alumina-filled dental composites showed less volumetric wear.

Therefore, it is important to consider the use of lubrication and the pH level of the surrounding environment when evaluating the tribological properties of dental materials using a pin-on-disk tribometer. It is recommended to choose a lubricant that mimics the oral environment and to test the materials under different pH conditions to evaluate their durability in the oral environment. In summary, the use of lubrication and the pH level of the surrounding environment are important factors that can affect the tribological properties of dental materials when evaluated using a pin-on-disk tribometer. It is important to carefully consider these factors to ensure accurate and representative results that reflect the real-world conditions in the oral environment.

2.4 Abrasive medium

In addition to tooth contact, the restoration wear should also be assessed in terms of contact with various foods. This is due to the fact that various food types and textures come into contact with dental restorations during mastication. During mastication, a food item that is hard may work as an abrasive whereas another item may work well as a lubricant. Understanding of the impact of food types and textures on the wear characteristics of restorative dental materials is therefore important in light of the positive versus negative effects of masticated food on dental restorations. Our everyday food contains a wide variety of components with varying textures. During mastication, these different textures of food may act as an abrasive or lubricant to the restorative materials. The wear of composite materials was greatly accelerated by the presence of abrasive material; however the effects varied depending on the kind of composite material[57].

The abrasive medium used in this method plays a crucial role in determining the accuracy and reliability of the results. When selecting an abrasive medium, it is important to consider its hardness, size, shape, and composition. The hardness of the abrasive medium should be similar to or higher than that of the dental material being tested to ensure that the abrasive can cause wear and damage to the material surface. The size and shape of the abrasive particles can also affect the tribological properties by altering the surface roughness and the contact area between the pin and the disk. The composition of the abrasive medium can also influence the results of the pin-on-disk tribometer. Some abrasive materials may react with the dental material, causing chemical changes and altering the wear rate and friction coefficient.

The effects of abrasive (calcium diphosphate) and fiber (methyl cellulose) components in abrasive medium on the wear of four composite resins (Clearfil AP-X, Z100 Restorative, SOLARE P, and SOLIDEX F) were evaluated[58]. Wear volume of all the composites increased due to presence of abrasive material in the medium. For AP-X and SOLARE P, the wear volume reduced due to presence of methyl cellulose in the medium. No significant effect was observed in Z100 and SOLIDEX F due to methyl cellulose. Ball-on-plate and pin-on-plate test apparatus was used to study the wear mechanism of TPH Spectrum and Resilab Master dental composite resins[32]. The tests were conducted with or without abrasive medium (aluminium oxide suspension). In ball-on-plate test, the wear was characterized by scratches induced by abrasive and/or adhesive mechanisms. But separate contributions of abrasive and adhesive wear could not be determined. In the pin-on-plate test, the wear was dominated by fatigue wear mechanism resulting in significant material loss.

Using the ACTA three-body wear machine, wear tests were conducted on composite materials (Herculite XR, PrismaFil, Silux Plus, P-s0, and Z100)[59]. During the wear tests, abrasive slurries comprising either beer, wine, 9 vol% ethanol, or water were utilised. Compared to the beer and water solutions, the wine and ethanol solutions dramatically increased wear. The wear between the wine and 9 vol% ethanol groups did not differ significantly, nor did the wear between the beer groups and the water groups. Furthermore, there was no discernible interaction between the various abrasive slurries and the composite type. The wear of two different materials (monolithic zirconia and cast cobalt chromium) was evaluated by performing the test on a pin-on-disc apparatus[19]. The wear test was performed in an abrasive medium of rice flour in slurry form. According to the findings, monolithic zirconia outperformed cobalt chromium in terms of wear resistance, which indicates the abrasive nature of cobalt chromium.

The impact of an enzymatic and an acidic medium on the in vitro deterioration of dental resin composites and an amalgam was examined[60]. In two-body and three-body wear circumstances, wear was assessed. The third body was food slurry with the same content and concentration as caries active plaque fluid, whether it was in water, an esterase solution, or an acid solution. Slurry was not tested in the two-body experiments. Both the enzyme and the acids failed to significantly affect wear under three-body wear circumstances. An abrasive test was performed to ascertain the impact of a carbonated beverage on the rate of wear as well as the abrasive effects of porcelain and a Ni-Cr alloy on the wear of human enamel[61]. When abraded on Ni-Cr and porcelain specimens, carbonated beverages dramatically increased dental specimen wear compared to artificial saliva. The wear of tooth specimens was highest when porcelain samples were placed in a medium of fizzy beverage.

The abrasive wear of the nanofilled, supra-nanofilled, nanohybrid and microhybrid composite resins in abrasive slurry of fluorite (fluorspar) powder mixed with distilled water was investigated[62]. SEM scans showed that while the performance of nanohybrid composites varied, nanofilled composites showed rather consistent wear surfaces with nanocluster protrusion. The abrasive enamel wear caused by three diamond-loaded toothpastes (Candida White Diamond: CWD, Swiss Smile Diamond Glow: SSDG, Emoform F Diamond: EFD) was investigated and compared it with a traditional toothpaste containing silica abrasive[63]. In comparison to conventional toothpaste, toothpastes with diamond fillings produced statistically considerably more abrasive wear. Significantly more enamel wear was seen in SSDG.

The Micro-scale TE 66 wear test equipment was used, which allowed for the replication of micro-abrasive wear, to conduct "In vitro" wear testing for three distinct dental composite restorative base resins (three-body rolling wear)[64]. Distillate water and synthetic saliva containing abrasive SiC particles were the two slurries used. When distilled water-SiC is utilised for the composites, the wear coefficient is low, but it is high for human enamel. However, only enamel exhibits high wear resistance with artificial saliva-SiC. One of the researchers investigated whether acidic toothpaste is, in fact, more abrasive than its neutral counterpart of otherwise equal composition and whether this increased abrasivity is mitigated by a buffered solution that simulates saliva[65]. Deionized water or a buffer solution comprising bicarbonate and phosphate were utilised as slurries for these tests. When water was utilised as the diluent along with the acidic toothpaste as opposed to the buffer solution, the results

showed a considerable increase in mean absolute dentin abrasion. With the neutral toothpaste, this was not the case.

In summary, the choice of abrasive medium is an important consideration when evaluating the tribological properties of dental materials using a pin-on-disk tribometer. The properties of the abrasive medium can affect the accuracy and reliability of the results by altering the surface roughness, wear rate, and friction coefficient. Therefore, it is important to carefully select an appropriate abrasive medium based on the properties of the dental material being tested and the specific tribological properties being evaluated.

2.5 Number of cycles

In a pin-on-disc tribometer, the number of cycles refers to the number of times the pin and disc have interacted with each other. The effect of the number of cycles on the tribological behavior of dental materials can depend on several factors such as the material composition, surface morphology, and contact conditions. The effect of the number of cycles will depend on the specific dental material being tested and the conditions of the test (such as load and speed). Generally, increasing the number of cycles can lead to an increase in wear, as the repeated sliding motion can cause material to be removed from the surfaces in contact. This can result in changes to the surface topography, such as the formation of grooves or scratches, which can affect the mechanical and biological properties of the material.

The three-body wear rates of five restorative dental composite materials subjected to various mastication cycles were investigated and compared with the findings for an amalgam material[66]. Five samples of each material were put through three-body wear tests using a computer-controlled chewing simulator with steatite balls acting as the antagonist (1.6 Hz, 49 N load; 120,000, 240,000, and 480,000 mechanical cycles; and thermal cycling between 5°C and 55°C at 5 min/cycle and 3000 cycles) while immersed in a slurry of poppy seeds (three-body wear environment). Most of the composite materials used in restorative dentistry exhibited good three-body wear resistance comparable to that of amalgam. After 480,000 chewing cycles, SEM analysis revealed micro-cracks and pits on the material surface. These microscopic fractures may be the continuation of underlying cracks in the material[67].

The wear of two distinct types of glass ionomer cement used in dentistry under sliding friction was examined after 28 days of storage in distilled water or Ringer's solution[68]. In sphere-on-plane contact circumstances, sliding friction was applied using a pin-on-disk tribometer at 5 N of normal load and 120 revolutions per minute. Replicas were run at 2500, 5000, and 7500 cycles throughout the 7500-cycle test. Between 0 and 2500 cycles, during the running-in period, wear rates of both materials steadily decrease. The wear rate for both materials equalizes and becomes constant after 2500 cycles. The tribological behaviour of the resin matrix in the resin-modified glass ionomer cement is weakened.

The wear of human enamel was studied in relation to a gold alloy, four dental ceramics (IPS Empress, IPS Empress 2, Duceram Plus, and Duceram LFC), and a laboratory-processed composite (Targis)[67]. After 150,000 and 300,000 cycles, the amount of wear on the enamel (dental cusps) and restorative materials (discs) was measured in water at 37°C under a standard load (20 N) and a chewing rate of 1.3 Hz. The results of this investigation suggest

that Targis might be a good substitute for ceramic since it is aesthetically pleasing and produces wear that is comparable to that of gold alloy.

Thermo-cycling techniques were used to model thermal fatigue using specific computer-controlled equipment in order to replicate environmental deterioration circumstances[69]. Specimens used in surface strength and wear tests underwent 10^4 hydrothermal fatigue cycles. The specimens were aged prior to thermo-cycling, which involved soaking them in synthetic saliva at a temperature of 37^o C for 30 days. It was discovered that microhardness and thermo-cycling fatigue directly correlated positively. The removal of material fragments in the form of flakes from the friction surface is the primary mechanism of wear of the experimental composites after thermo-cycling (spalling).

Overall, the effect of the number of cycles in a pin-on-disc tribometer will depend on a variety of factors, including the specific dental material being tested, the test conditions, and the properties being measured. It is important to carefully consider these factors when designing and interpreting experiments in order to accurately characterize the behavior of dental materials under sliding wear conditions.

However, the effect of the number of cycles on wear behavior can also depend on the type of material being tested. For example, some dental materials may exhibit an initial period of high wear followed by a period of steady-state wear, where the wear rate remains relatively constant over time. In these cases, increasing the number of cycles may not have a significant effect on the wear behavior once the steady-state wear regime is reached. In addition to wear behavior, the number of cycles can also affect other properties of dental materials, such as their surface roughness or friction coefficient. For example, increasing the number of cycles may lead to an increase in surface roughness, as the repeated contact and separation can cause material to be removed from the surface. Similarly, the friction coefficient may also be affected by the number of cycles, as the formation of wear debris or changes in surface topography can affect the frictional properties of the material[70,71, 72, 73].

2.6 Number of Specimens

The number of specimens can have a significant effect on the evaluation of tribological properties of dental materials using pin-on-disk tribometer. When testing the tribological properties of dental materials, it is important to use a sufficient number of specimens to obtain reliable and representative results. Using a small number of specimens can lead to inaccurate or misleading results due to the variability that can occur between individual specimens. In addition, a small sample size can also result in a lack of statistical power, making it difficult to draw meaningful conclusions from the data. On the other hand, using too many specimens can be impractical, time-consuming, and costly. It is important to strike a balance between the number of specimens used and the level of statistical significance required for the study.

In general, it is recommended to use at least 5-10 specimens for each group or condition being tested. This can help to reduce the effect of variability between individual specimens and increase the statistical power of the study. Additionally, it is important to randomize the selection of specimens to minimize the potential bias that can occur when selecting specimens based on their perceived quality or properties. In summary, the number of specimens used when evaluating the tribological properties of dental materials using pin-on-disk tribometer

can have a significant effect on the accuracy and reliability of the results. It is important to use an appropriate number of specimens that balances statistical significance with practical considerations such as time and cost[74,75].

2.7 Stylus Characteristics

When evaluating the tribological properties of dental materials using a pin-on-disk tribometer, the characteristics of the stylus can have a significant effect on the results obtained. The stylus is the component of the tribometer that is in direct contact with the sample being tested, and therefore its shape, size, sliding speed, descent or lifting speed and material can all affect the measurements obtained.

Some of the key stylus characteristics that can affect tribological testing of dental materials include:

2.7.1 Size and shape of stylus

The size and shape of the stylus material used in pin-on-disk tribometer testing for dental materials can vary depending on the specific experimental requirements and the materials being tested. However, there are some general guidelines that can be followed. Firstly, the stylus material should be hard and wear-resistant to prevent damage or deformation during testing. Secondly, the size and shape of the stylus can affect the contact area and the applied load, which can in turn affect the results obtained from the testing. A commonly used size for the stylus is 6 mm in diameter and 3 mm in height, but other sizes can also be used depending on the specific requirements of the experiment. The shape of the stylus can vary as well, with common shapes being cylindrical, conical, or spherical. Lastly, it is important to ensure that the stylus is well-aligned with the surface being tested to ensure accurate and consistent results[76,77].

2.7.2 Sliding speed of stylus

The sliding speed of the stylus in pin-on-disk tribometer testing for dental materials can also vary depending on the specific experimental requirements and the materials being tested. The sliding speed can influence the friction and wear behavior of the materials being tested. Generally, sliding speeds in the range of 0.1 to 1 m/s are used in tribological testing of dental materials. For example, when testing the wear resistance of dental materials, a lower sliding speed of 0.1 m/s may be used to simulate the relatively slow wear that occurs in the mouth. In contrast, when testing the frictional properties of orthodontic wires, a higher sliding speed of 1 m/s may be used to simulate the rapid sliding that occurs during orthodontic treatments[78,79].

Wear rate of polyester reinforced by glass and Kevlar fibers was investigated at various sliding speed using pin-on-disc tribometer[40]. The sliding speed of specimen was varied from 0.5 m/s to 2.5 m/s and it is found that as the sliding speed increases, the wear rate of specimen also increases.

2.7.3 Lifting speed of stylus

Pin-on-disk tribometry involves the measurement of the frictional and wear properties of materials by rubbing a pin against a rotating disk. During the test, the stylus is used to apply a load to the pin and the load is then lifted or descended to initiate or terminate the test. The lifting or descent speed of the stylus can affect the results obtained during the test in several ways. A higher lifting or descent speed may result in a more abrupt start or stop of the test, which could lead to differences in the initial and final contact conditions between the pin and disk. This could result in variations in the frictional and wear properties measured during the test. The lifting or descent speed can affect the contact time between the pin and disk. A faster lifting or descent speed may result in a shorter contact time, which could lead to incomplete transfer of materials between the pin and disk and consequently affect the frictional and wear properties measured. The lifting or descent speed can affect the surface damage to the materials being tested. A faster lifting or descent speed may result in more severe surface damage, which could affect the frictional and wear properties measured[78,79].

3 Conclusion

The evaluation of tribological characteristics plays an important role in the development and selection of dental materials that can withstand the dynamic and complicated oral environment. In order to evaluate the friction and wear behaviour of dental materials, a pin-on-disc tribometer is frequently utilized. The reliability and accuracy of the analyses can be influenced by number of factors, which can affect the findings of tribological testing. Surface roughness, applied load, lubrication or pH level, abrasive medium, number of cycles, number of specimens, and stylus characteristics are some of these factors. To ensure that accurate and reliable data is obtained, careful consideration of these factors is imperative. Additionally, it is essential to take into account the limitations and potential sources of error associated with the pin-on-disk tribometer. By carefully controlling these factors and being aware of potential limitations, researchers and clinicians can gain valuable insights into the tribological characteristics of dental materials and make appropriate decisions regarding their selection and use in clinical practice.

References

1. Sarode GS, Sarode SC. Abfraction: a review. J Oral Maxillofac Pathol. *Journal of oral and Maxillofacial Pathology*, 2013; 17(2):222.
2. Gupta A, Mohan I, Jude RR, Suryawanshi A. Behera N. Investigation of stress and tribological properties of dental composite materials using FEM Proc Inst Mech Eng. J: J Eng Tribol. 2023; 237(5):1070-1084.
3. Suryawanshi A, Behera N. Dental composite resin: a review of major mechanical properties, measurements and its influencing factors. *Materialwiss. Werkstofftech*. 2022; 53: 617.
4. NagemFilho H, D'azevedo MTFS, Nagem HD, Marsola, FP. Surface roughness of composite resins after finishing and polishing. Braz Dent J. 2003; 14:37-41.
5. Giannini M, Di Francescantonio M, Pacheco RR, Boaro LC, Braga RR. Characterization of water sorption, solubility, and roughness of silorane-and methacrylate-based composite resins,.Oper Dent. 2014; 39(3): 264-272.
6. Lins FCR, Ferreira RC, Silveira RR, Pereira CNB, Moreira AN, Magalhães CS. Surface roughness, microhardness, and microleakage of a silorane-based composite resin after immediate or delayed finishing/polishing. Int J Dent. 2016.

7. Shulev A, Roussev I, Karpuzov S, Stoilov G, Ignatova D, Von See C, Mitov G. Roughness measurement of dental materials. J Theor Appl Mech. 2016; 46(2): 27.
8. Yilmaz EC. Investigation of two-body wear resistance of composite materials for biomaterial application in oral environment: the influence of antagonist material. Mater Technol. 2020; 35(3): 159-167.
9. Sripetchdanond J. Leevailoj C, Wear of human enamel opposing monolithic zirconia, glass ceramic, and composite resin: an in vitro study. J Prosthet Dent. 2014; 112(5):1141–1150.
10. Jang YS, Nguyen TT, Ko YH, Lee DW, Baik BJ, Lee MH. Bae TS. *In vitro* wear behavior between enamel cusp and three aesthetic restorative materials: Zirconia, porcelain, and composite resin. J Adv Prosthodont. 2019; 11(1): 7–15.
11. Ghazal, M, Kern M.The influence of antagonistic surface roughness on the wear of human enamel and nanofilled composite resin artificial teeth. J Prosthet Dent. 2009; 101:342-349.
12. Preis V, Schmalzbauer M, Bougeard D, Schneider-Feyrer S, Rosentritt M. Surface properties of monolithic zirconia after dental adjustment treatments and in vitro wear simulation. J Dent. 2015; 15(43): 133-9.
13. Mehzabeen KR. Design and Development of a Biomimetic Dental Wear Test System and Characterizing Restorative Dental Materials, A PhD thesis, School of Aeronautical, Mechanical and Mechatronic Engineering, The University of Sydney, Australia, 2020.
14. Lawson NC, Janyavula S, Syklawer S, McLaren EA. Burgess JO. Wear of enamel opposing zirconia and lithium disilicate after adjustment, polishing and glazing. J Dent. 2014; 42(12): 1586-1591.
15. Mitov G, Heintze SD, Walz S, Woll K, Muecklich F, Pospiech P. Wear behavior of dental Y-TZP ceramic against natural enamel after different finishing procedures. Dent Mater. 2012; 28(8): 909-918.
16. Amer R, Kürklü D, Kateeb E, Seghi RR. Three-body wear potential of dental yttrium stabilized zirconia ceramic after grinding, polishing, and glazing treatments. J. Prosthet. Dent. 2014; 112(5): 1151-1155.
17. Turssi CP, Ferracane JL, Serra MC. Abrasive wear of resin composites as related to finishing and polishing procedures. Dent Mater. 2005; 21(7): 641-648.
18. Ratanapridakul K, Leinfelder KF, Thomas J. Effect of finishing on the in vivo wear rate of a posterior composite resin J Am Dent Assoc. 1989; 118(3): 333-5.
19. Kumar NA, Sampathkumar J, Ramakrishnan H, Mahadevan V. Comparative evaluation of wear resistance of CAD-CAM zirconia and cast cobalt chromium alloy for indirect restorations against human enamel - An in vitro study. Indian J Dent Res. 2020; 31: 537-45.
20. Di Fiore A, Stellini E, Basilicata M, Bollero P, Monaco C. Effect of toothpaste on the surface roughness of the resin-contained cad/cam dental materials: a systematic review. J Clin med 2022;11: 767.
21. Mörmann WH, Stawarczyk B, Ender A, Sener B, Attin T, Mehl A. Wear characteristics of current aesthetic dental restorative CAD/CAM materials: two-body wear, gloss retention, roughness and Martens hardness. J Mech behav Biomed Mater. 2013; *20*: 113-125.
22. Koizumi H, Saiki O, Nogawa H, Hiraba H, Okazaki T, Matsumura H. Surface roughness and gloss of current CAD/CAM resin composites before and after toothbrush abrasion. Dent Mater J. 2015; 34:881–887.

23. Flury S, Diebold E, Peutzfeldt A, Lussi A. Effect of artificial toothbrushing and water storage on the surface roughness and micromechanical properties of tooth-colored CAD-CAM materials. J Prosthetic Dent, 2017; 117:767–774.

24. Kamonkhantikul K, Arksornnukit M, Lauvahutanon S, Takahashi H. Toothbrushing alters the surface roughness and gloss of composite resin CAD/CAM blocks. Dent Mater J. 2016; 35:225–232.

25. de Andrade GS, Augusto MG, Simoes BV, Pagani C, Saavedra GSFA, Bresciani E. Impact of simulated toothbrushing on surface properties of chairside CAD-CAM materials: An in vitro study. J Prosthetic Dent. 2021; 125: 469.

26. Nima, G., Lugo-Varillas, J. G., Soto, J., Faraoni, J. J., Palma-Dibb, R. G., Correa-Medina A, Giannini M. Effect of toothbrushing on the surface of enamel, direct and indirect CAD/CAM restorative materials. Int J Prosthodont Endod. 2021; 34: 473–481.

27. Callaghan DJ, Vaziri,A, Nayeb-Hashemi H. Effect of fiber volume fraction and length on the wear characteristics of glass fiber-reinforced dental composites. Dent Mater. 2006; 22(1): 84–93.

28. Lambrechts P, Braem M, Vuylsteke-Wauters M. Vanherle G. Quantitative in vivo wear of human enamel, J Dent Res. 1989; 68(12):1752-4.

29. Oh WS, DeLong R. Anusavice KJ. Factors affecting enamel and ceramic wear: a literature review. J Prosthet Dent. 2002; 87(4): 451-9.

30. Kon M., Kakuta K, Ogura H. Effects of occlusal and brushing forces on wear of composite resins. Dent Mater J. 2006; 25(1): 183-94.

31. Dănăilă E, Benea L. The Effect of Normal Force on Tribocorrosion Behaviour of Ti-10Zr Alloy and Porous TiO_2–ZrO_2 Thin Film Electrochemical Formed. IOP Conf Ser Mater Sci Eng. 2017; 209(1): 012015.

32. De Souza JA, Dolavale LC, Camargo SA. Wear mechanisms of dental composite restorative materials by two different in-vitro methods. Mater Res. 2013; 16: 333-40.

33. Meena A, Bisht D, Yadav R, Saini S, Dangayach G, Patnaik A, Meena M. Fabrication and characterization of micro alumina zirconia particulate filled dental restorative composite materials. Polym Compos. 2022; 43(3):1526-1535.

34. Nagarajan VS, Jahanmir S, Thompson VP. In vitro contact wear of dental composites, Dent Mat. 2004; 20(1): 63–71.

35. Nagarajan VS, Hockey BJ, Jahanmir S, Thompson VP. Contact wear mechanisms of a dental composite with high filler content. J Mat Sc. 2000; 35:487-96.

36. Barange S, Hambire, U. Comparison and Optimization of Wear Rates of 3M Z350 (micro filled) and Filtek Z250 (micro hybrid) Dental Composite materials. Int.J Sci Dev Res. 2017; 5(2): 448-450.

37. Marquis P, Hu X, Shortall A. Two-body wear of dental composites under different loads. Int J prosthodont. 2000; 13(6): 473–479.

38. Tabatabaei MH, Arami S, Farahat F. Effect of mechanical loads and surface roughness on wear of silorane and methacrylate-based posterior composites. J Dent. 2016; 13(6):407–414.

39. Arsecularatne J, Chung N, Hoffman M. An in vitro study of the wear behaviour of dental composites. Biosurface Biotribology. 2016; 2(3):102-113.

40. Dawood JJ. A comparison between the wear rate behavior of polyester reinforced by glass and kevlar fibers. Eng Technol J. 2009; 27(11): 2273-2285.

41. Dziedzic K, Zubrzycka-Wrobel J, Jozwik J, Barszcz M, Siwak P, Chałas R. Research on tribological properties of dental composite materials. Adv Sci Technol Eng Syst J. 2016; 10(32): 144-149.

42. Badran A, Hamdy K, Rashed A. Hardness and tribological properties of pmma composite reinforced by hybrid graphene and TiO_2 nanoparticles used in dental applications. J Egyptian Soc Tribology. 2022; 19(2): 36-47.

43. Prasertwong S, Angkulpipat S, Srichumpong T, Suputtamongkol K, Thanachayanont C, Sola R, Heness G, Leonelli C, Chaysuwan D. Tribology, mechanical properties and coloration of a mica glass-ceramic. J Met Mater Miner. 2020; 30(2):83-90.

44. Suryawanshi A, Behera N. Tribological behavior of dental restorative composites in chewable tobacco environment. Proc Inst Mech Eng H P I MECH ENG H. 2020a; 234(10):1106–1112.

45. Suryawanshi A. Behera N. A Review: in vitro investigation of dental composite materials and tooth enamel by using pin-on-disc tribometer. In: Vasudevan, H., Kottur, V., Raina, A. (eds) Proceedings of International Conference on Intelligent Manufacturing and Automation. Lecture Notes in Mechanical Engineering. Springer, Singapore, 2020b. https://doi.org/10.1007/978-981-15-4485-9_50

46. Suryawanshi A, Behera, N. In-vitro wear measurements of dental composite influenced by chewable tobacco environment. Jurnal Tribologi. 2021; 29:84-95.

47. Suryawanshi A, Behera N. Prediction of wear of dental composite materials using machine learning algorithms. Comput Methods Biomech Biomed Eng. 2023a; 1–11. DOI: 10.1080/10255842.2023.2187671

48. Suryawanshi A, Behera N. Prediction of abrasive wears behavior of dental composites using an artificial neural network. Comput Methods Biomech Biomed Eng. 2023b; *26*(6): 710–720.

49. Alkassar Y, Agarwal V, Pandey R, Behera N. Influence of particle attrition on erosive wear of bends in dilute phase pneumatic conveying. Wear. 2021; 476:203594.

50. Yildirim Bicer AZ, Karakis D, Dogan A, Mert F. A comparison of wear rate of direct and indirect resin composites: A two-body wear abrasion test. J Compos Mater. 2015; 49(21):2599-2607.

51. Wu YQ, Arsecularatne JA. Hoffman M. Effect of acidity upon attrition–corrosion of human dental enamel. J Mech Behav Biomed Mater. 2015; 44: 23-34.

52. Turssi CP, Faraoni JJ, de Menezes M. Serra MC. Analysis of potential lubricants for in vitro wear testing. Dent Mater. 2006; 22(1):77-83.

53. Lakhdar S, Said B. Dental materials wear under different pH'. *Res J Med Sci*, 2007; 1(2):147-151.

54. Francisconi LF, Honorio HM, Rios D, Magalhaes AC, Machado MDA, Buzalaf MAR. Effect of erosive pH cycling on different restorative materials and on enamel restored with these materials. Oper Dent. 2008; 33(2):203-208.

55. Guo J, Bing Z, Yang J, Tsoi JK, Wang Y. Effect of roughness and acidic medium on wear behavior of dental resin composite. BMC Oral Health. 2022; 22(1):1-11.

56. Meena A, Mali HS, Patnaik A, Kumar SR. Investigation of wear behavior of nanoalumina and marble dust-reinforced dental composites. Sci Eng Compos Mater. 2019; 26(1):84-96.

57. Bourdiol P, Hennequin M, Peyron MA, Woda A. Masticatory Adaptation to Occlusal Changes. Front Physio.2020; 11: 263.

58. Kakuta K. Ogura H. Effects of abrasive and fiber components in medium on wear of composite resin. Dent Mater J. 2008; 27(5): 716-722.

59. Sarrett DC, Coletti DP, Peluso A. The effects of alcoholic beverages on composite wear. Dent Mater. 2000; 16(1) 62-67.

60. De Gee AJ, Wendt SL, Werner A, Davidson CL. Influence of enzymes and plaque acids on in vitro wear of dental composites. Biomater. 1996; 17(13):1327-1332.
61. Joshi N, Patil NP. Patil SB. The abrasive effect of a porcelain and a nickel–chromium alloy on the wear of human enamel and the influence of a carbonated beverage on the rate of wear. J Adv Prosthodont. 2010; 19(3):212-217.
62. Han JM, Zhang H, Choe HS, Lin H, Zheng G, Hong G. Abrasive wear and surface roughness of contemporary dental composite resin. Dent Mater J. 2014; 33(6): 725-732.
63. Hamza B, Abdulahad A, Attin T, Wegehaupt FJ. Diamond particles in toothpastes: in-vitro effect on the abrasive enamel wear. BMC Oral Health. 2022; 22(1):1-7.
64. Pena A, Gallardo EA, Morán A, Bravo JA. Vite M. Micro-abrasion study of some dental restorative materials and enamel. Proc Inst Mech Eng. J: J Eng Tribol. 2013; 227(5) 486-495.
65. Zehnder M, Masoch L, Gubler A, Mohn D, Attin T, Wegehaupt FJ. Buffer solution reduces acidic toothpaste abrasivity measured in standardized tests. Front Dent Med. 2020; 1:612298.
66. Yılmaz EC, Sadeler R. Investigation of three-body wear of dental materials under different chewing cycles. Sci Eng Compos Mater. 2018; 25(4):781-787.
67. Olivera AB. Marques M.M. Esthetic restorative materials and opposing enamel wear. Oper. Dent. 2008; 33(3): 332-337.
68. Villat C, Ponthiaux P, Pradelle-Plasse N, Grosgogeat B, Colon P. Initial sliding wear kinetics of two types of glass ionomer cement: a tribological study. Biomed Res Int. 2014.
69. Pieniak D, Walczak A, Walczak M, Przystupa K, Niewczas, AM. Hardness and wear resistance of dental biomedical nanomaterials in a humid environment with non-stationary temperatures. Mater. 2020; 13(5): 1255.
70. Drummond JL, Bapna MS. Static and cyclic loading of fiber-reinforced dental resin. Dental Mater. 2003; 19 (3): 226–231.
71. Hu X, Harrington E, Marquis PM, Shortall AC. The influence of cyclic loading on the wear of a dental composite. Biomater. 1999; 20(10): 907–912.
72. Wimmer T, Huffmann AM, Eichberge M, Schmidlin PR, Stawarczyk B. Two-body wear rate of PEEK, CAD/CAM resin composite and PMMA: Effect of specimen geometries, antagonist materials and test set-up configuration', Dent Mater. 2016; 32(6): e127–e136.
73. Yap AU, Teoh SH, Chew CL. Effects of cyclic loading on occlusal contact area wear of composite restoratives. Dent Mater. 2002; 18(2):149-158.
74. Heintze SD. How to qualify and validate wear simulation devices and methods. Dent Mater. 2006; 22: 712-7.
75. Mehzabeen KR, Boughton P, Kan WH, Ruys AJ, Guazzato M. Two-body wear test of enamel against laboratory polished and clinically adjusted zirconia. J Mech Behav Biomed Mater. 2020; 108:103760.
76. Condon JR, Ferracane JL. Effect of antagonist diameter on in vitro wear of dental composite. J Dent Res. 2003; 82 Special Issue A.
77. Krejci I, Lutz F, Zedler C. Effect of contact area size on enamel and composite wear. J Dent Res. 1992; 71:1413-14.
78. Heintze SD, Reichl FX, Hickel R. Wear of dental materials: Clinical significance and laboratory wear simulation methods -A review. Dent Mater J, 2019; 38(3):343–353.
79. McKinney JE, Wu W. Relationship between subsurface damage and wear of dental restorative composites. J Dent Res. 1982; 61:1083-1088.

B2. Yingchao Z, Haihuan G, Dan F, Tengjiaozi F, Danfeng C, Zuosen S, et al. New strategy for overcoming microleakage: an elastic layer for dental caries restoration. J Mater Chem B 2015;3(21):4401–5.

B1. Eltahlah D, Lynch CD, Chadwick BL, Blum IR, Wilson NH. An update on the reasons for placement and replacement of direct restorations. J Dent 2018;72: 1–7.

A1. Ferracane JL. Is the wear of dental composites still a clinical concern? Is there still a need for *in vitro* wear simulating devices? Dent Mater. 2006;22:689–692.

A2. Heintze SD, Ilie N, Hickel R, Reis A, Loguercio A, Rousson V. Laboratory mechanical parameters of composite resins and their relation to fractures and wear in clinical trials-A systematic review. Dent Mater. 2017;33:e101–e114.

A3. Heintze SD, Rousson V. Clinical effectiveness of direct class II restorations - a meta-analysis. J Adhes Dent. 2012;14:407–431.

C1. Van Noort R. Introduction to Dental Materials. Edinburgh: Mosby Elsevier, 2007

C2. Roulet JF. Degradation of dental polymers. Basel: Karger, 1987

C3 Heintze, S.D., Reichl, F.X. and Hickel, R., 2019. Wear of dental materials: Clinical significance and laboratory wear simulation methods—A review. *Dental materials journal*, *38*(3), pp.343-353

D1. Giusy Rita Maria La Rosa, Luigi Generali, CalogeroBugea, Hani F. Ounsi, GergelyBenyocs, Prasanna Neelakantan and Eugenio Pedulla, 'Application of Tribology Concept in Dental Composites Field: A Scoping Review', Journal of functional biomaterials, **2022**, *13*(4), 287; https://doi.org/10.3390/jfb13040287

D2. Wang, R., Zhu, Y., Chen, C., Han, Y., & Zhou, H. (2022). Tooth Wear and Tribological Investigations in Dentistry. *Applied bionics and biomechanics*, *2022*, 2861197. https://doi.org/10.1155/2022/2861197

D3. Condon, J. R., & Ferracane, J. L. (1997). Factors effecting dental composite wear in vitro. Journal of Biomedical Materials Research, 38(4), 303–313.doi:10.1002/(sici)1097-4636(199724)38:4<303::aid-jbm2>3.0.co;2-s

D4. Lanza A, Ruggiero A, Sbordone L. Tribology and Dentistry: A Commentary. *Lubricants*. 2019; 7(6):52. https://doi.org/10.3390/lubricants7060052