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Force degradation study on aligner plates immersed in various solutions

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KEYWORDS
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Abstract *Background/purpose:* The strength of aligners themselves has a high decay rate and is susceptible to accelerated degradation in the environment. The purpose of this study was to compare three types of invisible aligner films after being immersed in coffee, tea, cola, and red wine for seven days and to evaluate the changes in their strengths.
Materials and methods: Three types of invisible aligner plates with a thickness of 0.75 mm, i.e., Duran T (polyethylene terephthalate glycol, PETG), Biolon (polyethylene terephthalate, PET), and Zendura FLX (polyurethane, PU), were soaked in artificial saliva and four drinks (coffee, tea, cola, red wine) for 1, 4, and 7 days. The strength test was performed by using the three-point bending test method. The residual strength ratio for the same type of invisible correction film at the same time was separately recorded. The independent t-test was used to indicate significant differences at $P < 0.05$.
Results: The Biolon invisible correction film soaked in cola, red wine and artificial saliva showed significant differences on the 1st and 4th days ($P < 0.05$). The Duran T invisible correction film soaked in coffee and artificial saliva showed significant differences on the first day ($P < 0.05$). The Zendura FLX invisible correction film had a waterproof layer on the surface, and there was no significant difference between soaking in any drink and soaking in saliva ($P > 0.05$).
Conclusion: Invisible correction films with different ingredients soaked in solutions show a strength decay phenomenon, except for those with TPU ingredients.

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Introduction

The mechanical properties of an ideal aligner include low hardness, high transparency, high elasticity, low deformation force, high biocompatibility, and environmental stability.[1] Invisible orthodontic technology offers advantages in improving the alignment of anterior teeth, transverse relationships, and overbite issues.[2] The corrective force is generated by the deformation recovery of the aligner after it is compressed. Studies have shown that the relaxation curve of the aligner exhibits a relatively flat force decay, indicating that the aligner can maintain a stable strength over time.[3] Each step of wearing the aligner only generates a mild corrective force, which is intermittent in nature. Compared to traditional orthodontic techniques, this approach results in less root absorption.[4] A study based on the treatment outcome standards proposed by the American Board of Orthodontics showed a failure rate of 70.9% for invisible orthodontic cases,[5] which is higher than the 52% failure rate for traditional orthodontics.[2] This indicates that more than 70% of the treated cases require additional treatment, suggesting that the efficiency of tooth movement with clear aligners is lower than that with traditional braces.[6]

The strength of aligners themselves has a high decay rate and is susceptible to accelerated degradation in the environment. Reducing the degree of decay is a goal in aligner usage. Different companies have various approaches to tooth movement with aligners. Align Technology, the company behind Invisalign, recommends a tooth movement distance of 0.25—0.33 mm, while Raintree Essix suggests a movement distance of 0.5—1.0 mm.[7] Research has shown that in three-point bending tests, as the thickness or bending of the aligner plate increases (from 0.2 to 0.25, 0.5, 0.75, 1.0, 1.75, and 2.0 mm), the rebound force also increases.

The corrective force provided by aligners decays over time, and the rate of decay is influenced by humidity and temperature. Commonly used forming sheet materials include two types: polyethylene terephthalate glycol (PETG) and similar variants of polyethylene terephthalate (PET) and polyurethane (PU). is composed of PETG, a noncrystalline polymer made from PET and cyclohexanedimethanol (CHDM). It has high flexibility, fatigue resistance, impact strength, and chemical resistance. belongs to the PET category and has a higher crystalline composition, resulting in a higher structural strength. is composed of proprietary polyurethane (TPU) and exhibits high wear resistance, elasticity, and shear resistance and the ability to bond with other substances, providing diverse material properties.[8] It consists of hard and soft segments that, when subjected to external forces, create lateral forces perpendicular to the direction of the force and form small chunks that resist deformation. PU aligners, with their high adaptability to tooth surfaces, effectively transmit force.[9] They can provide sufficient and sustained light forces, which are beneficial for tooth movement. However, the color stability of PU is poorer.[10] This is due to the higher polarity (-NHCOO-) functional groups in PU compared to PETG and PVC, making it more prone to forming hydrogen bonds with hydrophilic pigments. In contrast, PETG and PVC have lower polarity with more -COO- and -C-O-C functional groups, making them less likely to form bonds with hydrophilic pigments.

Zendura FLX is a three-layered PU material with an outer waterproof layer encapsulating the inner PU layer. According to research, when F22 (TPU) and Duran (PETG) aligner films were subjected to continuous 7 mm deformation in water for 24 h and tested using a three-point bending test, the final residual stresses were found to be 45.5% and 38% of the original stresses, respectively.[4] This indicates that TPU has a stronger ability to maintain a stable force. Additionally, a study showed that a 0.75 mm Duran aligner film soaked in water and subjected to force for 24 h experienced a 50% force decay, while a nonloaded forming sheet soaked in water only experienced a 14% decay.[11] Therefore, it can be inferred that the immersion of aligners in water under force increases the degree of force decay in the aligners.

The purpose of this study was to compare three types of invisible aligner films, namely, Duran T (PETG), Biolon (PET), and Zendura FLX (TPU), after being immersed in coffee, tea, cola, and red wine for seven days and to evaluate the changes in their strengths.

Materials and methods

Three types of invisible aligner films (as shown in Table 1) were immersed in 150 ml of artificial saliva (Table 2), Coca-Cola, tea (Lipton black tea), coffee (UCC coffee), and wine (rose red wine). A total of 60 samples were prepared, with 6 repetitions, resulting in 360 aligner films in total. The diameter of the aligner films was 125 mm, with a thickness of 0.75 mm. For this experiment, aligner films of size 10 mm*40 mm were cut for use as the samples.

All samples were soaked in the respective liquids at room temperature for 0, 1, 4, or 7 days. After removal, they were air-dried and subjected to a three-point bending test using a digital push-pull force gauge (ZHIQU Precision Instruments, Dongguan, Guangdong Province, China) (Fig. 1). The principle of the three-point bending test is to place a rectangular or circular specimen between two support points and apply a concentrated load in the middle, causing the specimen to undergo bending deformation. By measuring the dimensions of the specimen, span distance,

Table 1 Materials of invisible aligner sheets.

Aligner Brand	Composition	Manufacturer
Duran	Polyethylenterephthalat-Glycol Copolyester (PET-G)	Scheu Dental GmbH (Am Burgberg, Iserlohn, Germany)
Biolon	Polyethylene Terephthalate (PET)	Dreve Dentamid GmbH (Max-Planck-Straße,Unna, Germany)
Zendura FLX	Thermoplastic Urethane (TPU)	Zendural Dental (Lakeview Blvd, Fremont, CA, USA)

Table 2 Composition of artificial saliva.

Materials	Concentration	Materials	Concentration
NaCl	0.6 g/L	$Na_2HPO_2 \cdot 12H_2O$	0.856 g/L
KCl	0.72 g/L	KSCN	0.06 g/L
$CaCl_2 \cdot 2H_2O$	0.22 g/L	$NaHCO_3$	1.5 g/L
KH_2PO_4	0.68 g/L	$C_6H_8O_7$	0.03 g/L

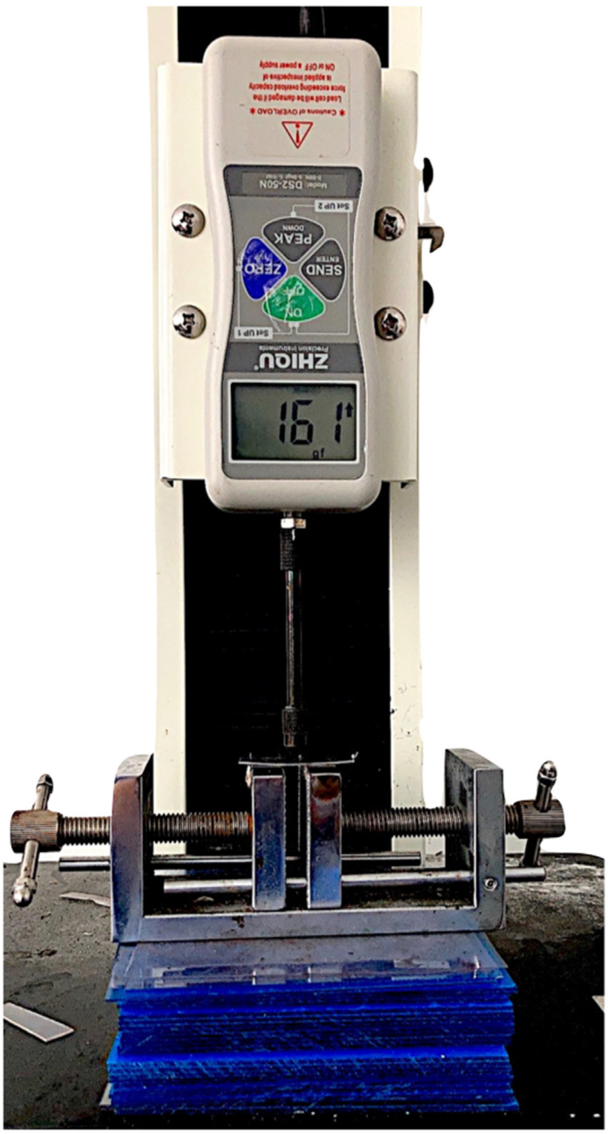

Figure 1 The three bending point test by digital push-pull force gauge.

load, and deflection, the bending stress and strain can be calculated, providing relevant mechanical parameters.

The test parameters used in this experiment were a span distance of 10 mm, a downward displacement of 3 mm, a downward speed of 5 cm/min, and a preload of 10 g.[11] The statistical analysis was performed using independent t tests, and a significance level of $p < 0.05$ was used to determine the presence of differences between the data.

Results

As shown in Table 3 and Fig. 2, for Biolon forming sheets, there were significant differences between the samples soaked in wine and those soaked in artificial saliva on the first and fourth days. Similarly, significant differences ($P < 0.05$) were observed between the samples soaked in Coca-Cola and those soaked in artificial saliva on the first and fourth days. Duran T forming sheets showed a significant difference ($P < 0.05$) between the samples soaked in coffee and those soaked in artificial saliva on the first day. In contrast, there were no significant differences ($P > 0.05$) observed for Zendura FLX forming sheets between the samples soaked in any of the beverages and the samples soaked in saliva.

Discussion

Zendura FLX immersed in any beverage showed no significant difference compared to immersion in artificial saliva, suggesting that its waterproof layer reduces the impact on its strength. PETG and PET have high chemical resistance, and within 7 days, their structures are minimally affected by the composition of the immersion liquid. Therefore, we believe that the strength degradation is mainly influenced by the water absorption of the forming sheets. This can be explained by the phenomenon of water absorption following Fick's law of diffusion.[12] When water molecules enter the dry forming sheets, the permeation rate is initially fast, but as the water absorption increases, the permeation rate gradually decreases until it reaches saturation equilibrium. When all the aligner sheets were immersed in beverages, there were no significant differences in residual strength compared to immersion in artificial saliva by the 7th day. We attribute this to the strength degradation of the forming sheets being related to water absorption.

By the 7th day, the water absorption of all the forming sheets reached saturation equilibrium, resulting in no significant differences in the residual strength ratios. On the other hand, for Biolon forming sheets, immersion in wine or Coca-Cola showed significant differences compared to immersion in artificial saliva on the first or fourth day, but no significant differences were observed after 7 days. This may be due to its amorphous nature, where the strength is more affected by water absorption. Wine and Coca-Cola affect the water absorption rate of Biolon but do not change the water absorption saturation level. Therefore, significant differences exist on the first and fourth days between immersion in wine or Coca-Cola and immersion in artificial saliva, but after 7 days, when the water absorption reaches equilibrium for all three cases, there are no significant differences in strength.

One study showed that after 24 h of force application in water, the residual strength of Duran T and F22 decreased by 54.4% and 62%, respectively.[4] However, the results of this study showed that after one day of immersion in the solution, the strength of the aligner sheets was between 75 and 90% of the original strength. In another study, three different thermoplastic aligner materials were selected: Duran (Scheu, Iserlohn, Germany), Erkodur (Pfalzgrafenweiler Co.,

Table 3 Average residual strength ratios of the three materials immersed in different liquids (Mean ± Standard Deviation).

Brands	Solutions	Initial force	Day 0	Day 1	Day 4	Day 7
Biolon	Saliva	337.83 (16.94)	100.0 (0.00)	77.53 (4.05)	69.1 (8.68)	62.86 (3.9)
	Coffee	351.33 (20.46)	100.0 (0.00)	79.29 (11.26)	67.13 (7.92)	59.91 (3.06)
	Tea	345.0 (18.15)	100.0 (0.00)	78.08 (4.48)	68.79 (5.59)	62.96 (5.05)
	wine	346.83 (12.98)	100.0 (0.00)	86.44 (6.38)*	79.0 (5.48)*	69.34 (8.71)
	Cola	356.83 (25.79)	100.0 (0.00)	89.79 (5.29)**	87.48 (6.27)**	65.8 (4.84)
Duran T	Saliva	321.67 (32.18)	100.0 (0.00)	94.46 (3.98)	78.92 (9.64)	73.64 (8.76)
	Coffee	323.0 (35.59)	100.0 (0.00)	86.72 (7.36)*	74.61 (7.88)	73.64 (4.36)
	Tea	332.0 (23.11)	100.0 (0.00)	88.18 (7.4)	80.35 (4.74)	66.68 (2.85)
	wine	329.67 (21.63)	100.0 (0.00)	88.99 (9.94)	74.7 (7.75)	69.6 (4.09)
	Cola	319.33 (16.42)	100.0 (0.00)	90.04 (5.53)	84.99 (3.94)	72.97 (5.7)
Zendura FLX	Saliva	218.0 (30.13)	100.0 (0.00)	82.15 (9.72)	74.85 (9.13)	64.75 (7.32)
	Coffee	223.5 (21.27)	100.0 (0.00)	0.77 (0.11)	0.72 (0.09)	0.65 (0.1)
	Tea	228.17 (16.45)	100.0 (0.00)	0.85 (0.11)	0.78 (0.13)	0.64 (0.17)
	wine	247.67 (24.83)	100.0 (0.00)	0.82 (0.08)	0.72 (0.05)	0.57 (0.12)
	Cola	222.17 (27.08)	100.0 (0.00)	0.85 (0.09)	0.79 (0.09)	0.73 (0.1)

*: $P < 0.05$; **: $P < 0.01$.

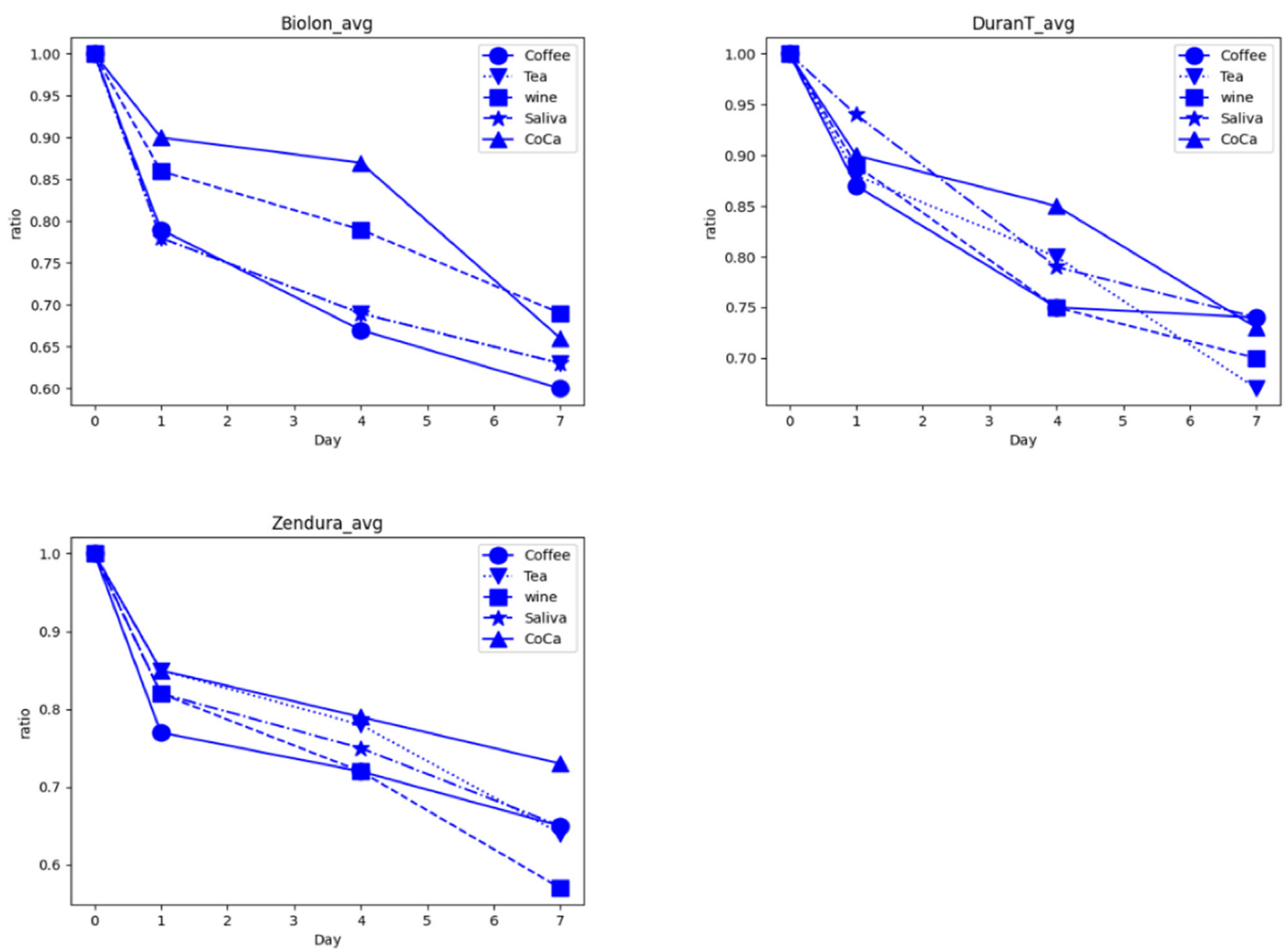

Figure 2 Average residual strength ratios of the three aligner sheet materials immersed in different liquids, showing a decrease in strength over time.

Erkodent, Germany), and Track (Forestadent Co., Baden-Wurttemberg, Germany). Using a 0.75 mm Duran material for forming sheets, a 7 mm deformation was applied in a three-point bending test. The study found that all three selected polymers released significant stress within 24 h. Duran had the highest stress release at 18.96 N/cm^2, followed by Erkodur at 13.96 N/cm^2 and Track at 13.18 N/cm^2. After 24 h, the residual stress was 86%.[13] Another study examined polyethylene terephthalate glycol (PETG) Duran® samples of different thicknesses immersed in water for 24 h and subjected to constant loading in a three-point bending test. The bending force decreased by 50%.[11] In a study using 0.75 mm Duran T as the aligner sheet, when the sheet was expanded by 0.2 mm and immersed in artificial saliva for 1, 4, and 7 days, the residual strengths measured with a thin-film pressure sensor were 94%, 90%, and 85%, respectively.[14] In this study, when 0.75 mm Duran T aligner sheets were immersed in artificial saliva for 1, 4, and 7 days and subjected to a three-point bending test, the measured residual strengths were similar at 94%, 79%, and 74%, respectively. Although the thickness of the aligner sheets decreases after thermoplastic forming, the formed shape limits the release of residual stress, resulting in a higher rate of strength degradation in the three-point test compared to the forming aligners.

Polymer degradation occurs due to water absorption, which leads to flattening of the stress–strain curve and a decrease in the elastic modulus. Water molecules penetrate the polymer matrix, increasing the molecular mobility in the amorphous regions and causing stress relaxation.[15] The permeation of water into the polymer reduces its glass transition temperature (Tg) and promotes molecular movement within the matrix, indirectly leading to degradation.[15] The water absorption of aligner sheets affects the rate of strength degradation. The water saturation level at 37 °C is approximately 15 $\mu g/mm^3$ for PU and 8 $\mu g/mm^3$ for PETG. Higher water absorption leads to greater release of polymer molecules over time, which affects the mechanical structure.[16]

A study on the long-term (six month) immersion of aligner sheets showed the changes in TPU after immersion in water at 70 °C. The water absorption of TPU stabilized at 1.5% after 56 h, and FTIR spectroscopy revealed a decrease in the concentration of carbonyl groups with or without hydrogen bonding in TPU. The study found that water absorption in TPU followed Fick's law, and with increased immersion time, the hardness, tensile strength, and elastic modulus of TPU decreased, while the elongation at break increased, suggesting irreversible degradation of the polymer material.[17]

It is concluded that Zendura FLX aligner sheets, with their waterproof layer, showed no significant difference after immersion between any beverage and artificial saliva. Biolon aligner sheets exhibited significant differences when immersed in wine or Coca-Cola compared to immersion in artificial saliva on the first and fourth days. Duran T aligner sheets showed a significant difference between immersion in coffee and immersion in artificial saliva on the first day.

Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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