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RESEARCH

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Effects of simulated intraoral temperatures and wet environments on the stress relaxation properties of thermoplastic aligner materials

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Abstract

Introduction Thermoplastic aligner materials are made from copolymers, and in the oral environment, their mechanical properties change over time. The effects of intraoral temperatures and the wet environments on the stress relaxation properties of these materials remain poorly understood. The aim of this study is to investigate the separate effects of the temperature and wet environment on the stress relaxation behavior of five available commercial orthodontic thermoplastic materials consisting of three chemical compositions.

Method A modified temperature-controlled water bath system was used to eliminate the confounding effect of water. The residual stresses of five commercial orthodontic thermoplastic materials with different chemical compositions (Biolon, Duran, and Erkodur (PETG), Essix ACE (copolyester), and Essix C+ (PP/PE)) were examined at room temperature (22 °C), 37 °C, and 55 °C. After the materials were immersed in deionized water and artificial saliva for two weeks (37 °C), the 30 min stress relaxation curves of the five materials were measured.

Results Compared with those at room temperature (22 °C), the stress relaxation rates of the five materials increased and ranged from 0.7% to 18.11% at 37 °C and from 20.54% to 88.31% at 55 °C, and Ekodur and Essix ACEs exhibited relatively smaller increases. After two weeks of immersion in deionized water and artificial saliva, the stress relaxation rate of Essix ACE significantly decreased ($p < 0.05$), whereas that of the other four materials did not significantly change.

Conclusion Elevated intraoral temperature accelerated the stress relaxation of thermoplastic aligner materials. The intraoral liquid immersion had no accelerating effect on the stress relaxation of any of the tested materials and even had a significant decelerating effect on that of Essix ACE.

Keywords Orthodontic thermoplastic material, Stress relaxation, Clear aligner, Simulated intraoral environment

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Introduction

Thermoplastic materials, such as night guards, bleaching trays, bruxism splints and retainers, have been widely used in dental medicine because of their excellent formability, superelasticity and abrasive resistance. Over the past two decades, clear aligners (CAs) have become popular among patients and orthodontists and have advantages such as improved good aesthetics, longer intervals between appointments, greater comfort and oral hygiene.

Clear aligner technology is based on three fundamental technologies: virtually designing tooth movement steps, manufacturing dental models of each step by CAD/CAM, and vacuum-forming or thermoforming a series of clear aligners. According to different manufacturers, a set of clear aligners is instructed to be worn 7 to 14 days and to be worn for more than 22 h a day. As an oral appliance, intraoral environments play an important role in its efficacy.

Thermoplastic aligner materials are copolymer materials that are viscoelastic and exhibit characteristics of stress relaxation.

Stress relaxation refers to the decrease in stress over time when a polymer is subjected to constant deformation at a specific temperature. This phenomenon causes difficulty in the predication of the force exerted and in the further understanding of the precise mechanism of aligner orthodontics.

The mechanism of aligner orthodontics is different from that of fixed orthodontics, the distance between the actual tooth position and the intended tooth position causes deformation of thermoplastic material and then generates internal stress. This, in turn, initiates tooth movement. The appropriate orthodontic force is a continuous light force, which requires thermoplastic materials to have a suitable hardness, high yield strength and flat stress relaxation curve.

In the past few years, numerous studies have investigated the mechanical properties of orthodontic thermoplastic materials [1–3]. However, studies on long-term mechanical behavior are limited [4–6].

In addition, few studies have considered the effects of the oral environment on mechanical properties. The intraoral environment is characterized by temperature variations during hot beverage consumption, cyclic loading from appliance removal and reinsertion, continuous cold working due to mastication, and microbial activity; this environment inevitably impacts the mechanical properties of thermoplastic materials [7]. Elevated intraoral temperatures and wet environments are two fundamental intraoral environments.

Fang reported that the stress relaxation process of orthodontic thermoplastic materials was accelerated in a 37 °C water bath [8]. Ihssen reported that thermocycled and water-immersed materials had lower Young's moduli than the control materials [9]. Iijima reported that the mechanical properties of five commercial thermoplastic materials significantly decreased after 2500 thermal cycles [10]. Kwon reported no significant difference in force delivery properties after thermocycling in 55 °C distilled water [2]. However, the above studies tested samples in a hygrothermal environment, the effect of oral temperature alone on material stress relaxation remains unknown, and the role of the intraoral wet environment in stress relaxation also needs to be addressed [11].

In this study, we examined the influence of temperature and the wet environment on the stress relaxation behavior of five commonly used thermoplastic aligner materials available on the market: Biolon, Duran, Erkodur, Essix ACE and Essix C+.

Materials and methods

Specimen preparation

The details of the five types of commercial thermoplastic materials used are listed in Table 1. Biolon (Dreve Dental, GmbH), Duran (Scheu Dental, GmbH) and Erkodur (Erkodent, GmbH) are composed of polyethylene terephthalate-1,4-cyclohexanedimethylene-terephthalate (PETG). Essix ACE (Dentsply Raintree Essix, Inc.) is composed of copolyester, whereas Essix C+ (Dentsply Raintree Essix, Inc.) is a mixture of

Table 1 Details of the five tested thermoplastic materials

abbreviation	type	manufacturer	chemical composition	chemical formula	Thickness (mm)
B	Biolon	Dreve Dental, GmbH	PETG	[COC6H4COOCH2CH2O]n	1
D	Duran	Scheu Dental, GmbH	PETG	[COC6H4COOCH2CH2O]n	1
E	Erkodur	Erkodent, GmbH	PETG	[COC6H4COOCH2CH2O]n	1
ACE	Essix ACE	Dentsply Raintree Essix, Inc	Copolyester	[COOCH2CH(CH3)O]n	0.89
C+	Essix C+	Dentsply Raintree Essix, Inc	PP/PE	[CH2CH(CH3)]n, [CH2CH2]n	1.02

Chemical composition is obtained from the manufacturers' Material Safety Data Sheet

Abbreviations: *PETG* Polyethylene terephthalate-1,4-cyclohexanedimethyleneterephthalate, *PP* Polypropylene, *PE* Polyethylene polypropylene (PP) and polyethylene (PE). All of the above materials are single-layer sheets.

For subsequent uniaxial tensile tests and stress relaxation tests, the membrane materials were trimmed into standardized dumbbell-shaped specimens using the punching/stamping technique, according to ISO standard 527–3 type 5 [12]. The middle part designed for testing was 33 mm ± 2 mm in length and 6 mm ± 0.4 mm in width (Fig. 1).

For the preliminary uniaxial tensile test, five replicates of each material were used, for a total of 25 specimens ($n = 25$). For the stress relaxation test, each material in the different treatment groups had five replicates: 75 specimens for the temperature-related test ($n = 75$) and 75 specimens for the wet environment test ($n = 75$).

Modified temperature-controlled water bath system

A self-designed temperature-regulated water bath system based on Fang's design [8] was constructed and consisted of three parts (Fig. 2):

(1) A metal water cup with a diameter of 50 mm and a height of 75 mm was used, with an inlet pipe and an outlet pipe located on the sidewall near the bottom and top, respectively.
(2) A peristaltic pump injected heated water from the inlet pipe at the bottom of the cup and pumped out

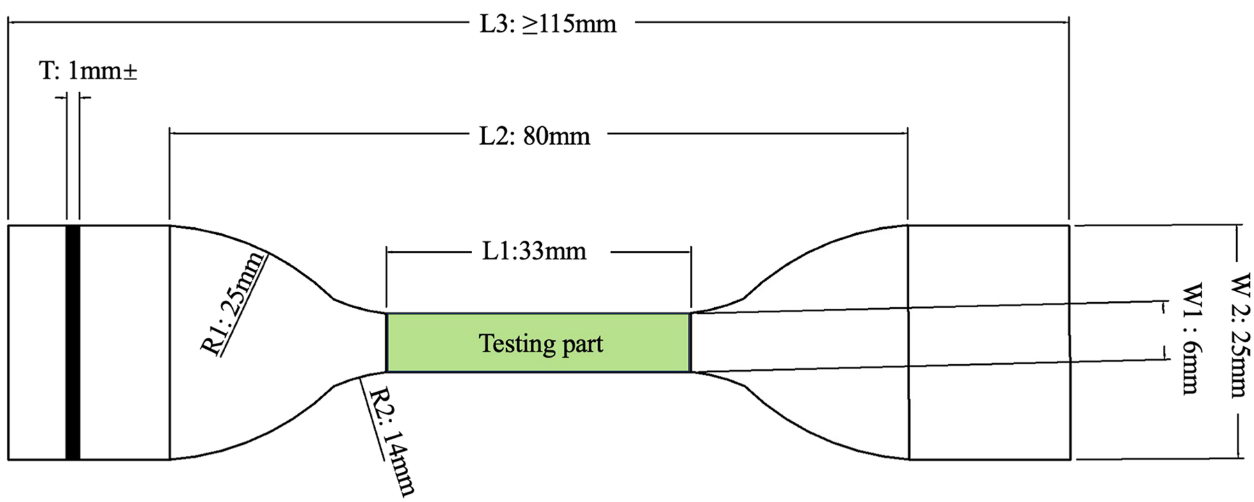

Fig. 1 Dumbbell-shaped specimens according to ISO standard 527–3 type 5. L1: length of testing part, 33 mm ± 2 mm; L2: length between clasps, 80 mm ± 5 mm; L3: total length, ≥ 115 mm. W1: width of testing part, 6 mm ± 0.4 mm; W2: total width, 25 mm ± 1 mm. T: thickness, 1 mm ±. R1: large radius, 25 mm ± 2 mm; R2: small radius, 14 mm ± 1 mm. The green rectangular part in the middle of specimen represents testing part

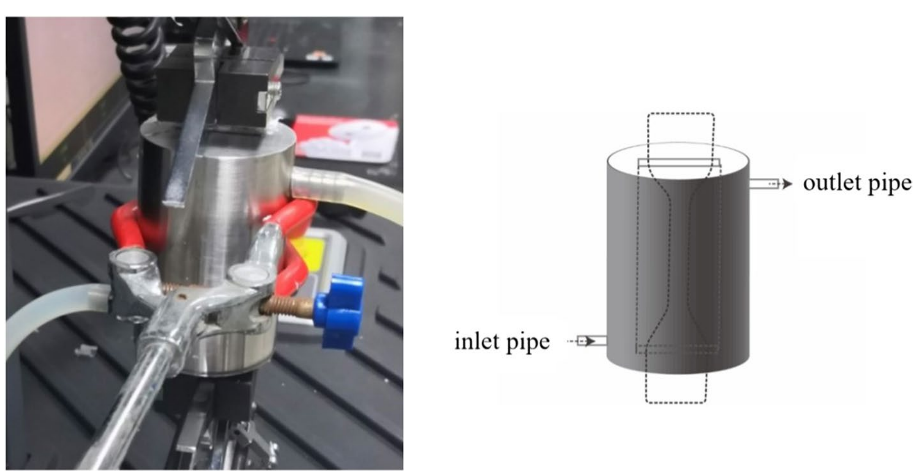

Fig. 2 Photograph and diagram of the temperature-controlled water bath system

effluent water from the outlet pipe at the top. The water flow direction ensured that the cup remained full of water.

(3) The box chamber shared the same axis and height as the metal cup, with two parallel rectangular openings that were 27 mm long and 2 mm wide at the top and bottom; this enabled the specimen to be clamped through the openings. The specimens were isolated from direct contact with heated water, preventing liquid disturbance during testing.

(4) The specimens were preheated in the chamber for 3 min to ensure complete heat conduction. The temperature of each sample was recorded using an infrared thermometer within 2 s.

Intraoral temperature simulation

The standardized specimens were divided into three groups. In the control group, The specimens were examined in an ambient environment. In the 37 °C group, the specimens were heated by the modified water bath system. When people consume hot food or beverages, the intraoral temperature can be elevated to 55 °C; thus, we also set a 55 °C group to simulate this condition.

Intraoral wet environment simulation

The standardized specimens were divided into three groups. In the control group, the specimens were stored in dry air. In the deionized water group, the specimens were immersed in 37 °C deionized water for 2 weeks. In the artificial saliva group, the specimens were immersed in 37 °C artificial saliva for 2 weeks. The immersion procedure is described below.

First, the ziplock bags were filled with distilled water or artificial saliva (ISO/TR10271, Kechuangwei, Shandong, China). Second, the specimens were carefully placed in the ziplock bags, and the testing part of the specimens was ensure to have no overlap. Third, the bags were sealed, the air bubbles were carefully expelled, and prepared ziplock bags were then placed into a 37 °C water bath tank.

The incubation liquid in the ziplock bags was renewed every other day, and the specimens were checked to ensure that their testing parts did not overlap upon liquid replacement.

The composition of the artificial saliva was as follows: NaCl 0.4 g/L, KCl 0.4 g/L, $CaCl_2 \cdot H_2O$ 0.795 g/L, urea 1 g/L, $Na_2S \cdot 2H_2O$ 0.005 g/L, $NaH_2PO_4 \cdot H_2O$ 0.78 g/L. The pH was adjusted to 6.88 to simulate the commonly neutral intraoral pH. (Supplementary Fig. 1).

Uniaxial tensile test and stress relaxation test

Given the variation in material types and thicknesses, their static mechanical properties are expected to differ. Therefore, a uniaxial tensile test was conducted; here, the tested specimens were placed in a standard environment (25 °C, 50% relative humidity) for 1 day before testing and then stretched at a speed of 5 mm/min using a Universal Mechanical Testing Machine Instron 6800 (Instron, Canton, MA, USA) until they broke (Supplementary Fig. 2).

The initial deflection of the following stress relaxation test was set as a quarter of the ultimate tensile strength. Therefore, the initial deflection is ensured to be considerably small to maintain linear viscoelasticity [13] (Table 2).

The specimens were stretched using the same universal mechanical testing machine to a certain strain at a speed of 5 mm/min and then held at a constant strain for 5 h in the temperature effect test and for 20 min in the wet environment test.

Statistical analysis

For each specimen, the normalized residual stress was calculated using the formula (Nn/N0) × 100, where Nn is

Table 2 1/4 tensile strength and corresponding tensile strain in room temperature

abbreviation	type	tensile modulus	ultimate tensile strength	1/4 ultimate tensile strength	deflection at 1/4 ultimate tensile strength	strain at 1/4 ultimate tensile strength
		(GPa)	(MPa)	(MPa)	(mm)	(%)
B	Biolon	2.05 ± 0.07	51.73 ± 1.80	12.93	0.29	0.87
D	Duran	2.01 ± 0.05	52.80 ± 1.14	13.2	0.31	0.94
E	Erkodur	2.07 ± 0.06	59.76 ± 0.51	14.94	0.33	1
ACE	Essix ACE	1.82 ± 0.06	47.06 ± 0.13	11.77	0.3	0.92
C+	Essix C+	1.06 ± 0.05	33.82 ± 2.43	8.46	0.25	0.76

The values are represented as the mean ± standard deviation, for their normal distribution

Tensile modulus (GPa): refers to the ratio of stress to strain within the elastic limit of a material

Ultimate tensile strength (MPa): refers to the maximum tensile force that a material can withstand per unit area when subjected to tensile force

1 GPa = 1000 MPa

the residual stress value at relaxing time Tn, and N0 is the initial stress value at zero minutes.

The statistical analysis was performed using SPSS 27.0 software (IBM Corp., Armonk, Ny, USA). Normality and homogeneity of variance were assessed by the Kolmogorov–Smirnov test and the Levene test, respectively. All results were normally distributed and were analyzed via one-way analysis of variance (ANOVA). $P < 0.05$ was considered statistically significant. The data are presented as the means ± standard deviations.

All curves were generated by Origin Software 15.0 (OriginLab Corp., Northampton, Ma, USA.)

Results

Effect of temperature on the stress relaxation of thermoplastic materials

Figure 3 illustrates the time-dependent stress–strain behaviors of the five materials and shows a decrease in the normalized residual stress at room temperature, 37℃ and 55℃. At each time point, the residual stress under heated conditions was notably lower than that at room temperature; these results indicated that increasing the temperature increased the stress relaxation rate of orthodontic thermoplastic materials.

Biolon (Fig. 3a) exhibited a low stress relaxation rate at 37 °C, which was similar to its performance under ambient conditions, and no distinct difference was observed in residual stress after 3 h (Table 3: 88.31% & 87.56%). However, its relaxation rate sharply increased at 55 °C, and the residual stress decreased to zero at 2.5 h. Duran (Fig. 3b), Erkodur (Fig. 3c) and Essix ACE (Fig. 3d) demonstrated similar behavior at 37 °C, and the residual stress remained above 80% after 3 h of relaxation. However, their performance varied significantly at 55 °C. The residual stress of Duran decreased to zero after 2.5 h, that of Erkodur remained at 40–50% after 3 h, and that of Essix ACE decreased to 20%. Essix C+ (Fig. 3e) exhibited early-stage stress relaxation under all three temperature conditions. Its residual stress decreased to 62.55% (3.17 MPa) in the ambient environment, decreased to 44.44% (1.86 MPa) at 37 °C, and decreased to 42.01%(1.14 MPa) at 55 °C.

At room temperature and 37℃ (Fig. 3f and g), most materials presented relatively low stress relaxation rates, and the residual stress remained at approximately 80–90% after 5 h of relaxation, with the exception of for Essix C+, which had a more substantial decrease to 45–55%. At 55℃ (Fig. 3h), the differences in the stress relaxation of the materials became more pronounced. Biolon and Duran exhibited extremely rapid relaxation, and the residual stress decreased to zero after 2.5 h. Essix C+ and Erkodur behaved relatively well and maintained approximately 40% of their initial stress. Essix ACE demonstrated a stress relaxation curve that fell between those of the other four materials and retained 20% of their initial stress after 5 h.

Overall, Erkodur and Essix ACE are relatively stable materials among the tested materials within the intraoral temperature range.

Effect of the wet environment on the stress relaxation of thermoplastic materials

Figure 4 shows the time-dependent stress–strain behaviors of five types of thermoplastic materials in dry environments, deionized water and artificial saliva. The residual stress rapidly decreased during the first 8–10 min for all the materials.

The wet environment had varying effects on the stress relaxation properties of the materials. The relaxation curves of Duran and Essix C+ significantly overlapped in both dry and wet environments; these results indicated that the wet environment had little effect on their stress relaxation behavior. In contrast, Erkodur displayed wide variations in its relaxation curves, although the wet environment had no significant effect on its residual stress after 20 min of relaxation. The residual stress of Biolon and Essix ACE was greater in wet environments than in dry air. Notably, the residual stress of Essix ACE in deionized water and artificial saliva was significantly greater than that in dry air, although no significant difference was observed between the two environments (Table 4).

Discussion

The clear aligner (CA) was extensively developed after Kingsley first invented tooth positioners in 1945 [14]; however, its precision and efficiency of tooth movement are still not satisfactory [15–17]. Successful CA treatment is based on proper case selection [18–20], correct treatment planning and, most importantly, the superior mechanical properties of orthodontic thermoplastic materials.

Previous in vivo studies indicated that orthodontic force drastically decreased in the first few days during the first two days of application [21, 22]. However, the force degradation observed in vivo was influenced not only by the material's stress relaxation but also by periodontal ligament compression and tooth movement. The effect of a single factor on the stress relaxation behavior of thermoplastic materials could be investigated only by simulating the intraoral environment in vitro.

Gale reported that after 1000 thermocycles between 55 °C and 20 °C, the ultimate tensile strength of Essix C+ decreased to 42.2 MPa [23]. Iijima reported a 34% reduction in the stress relaxation rate after 30 min of thermocycling [10]. Lombardo reported that the residual stress value of Duran was 75%–80% after three hours of relaxation. In our study, the stress relaxation rates of the

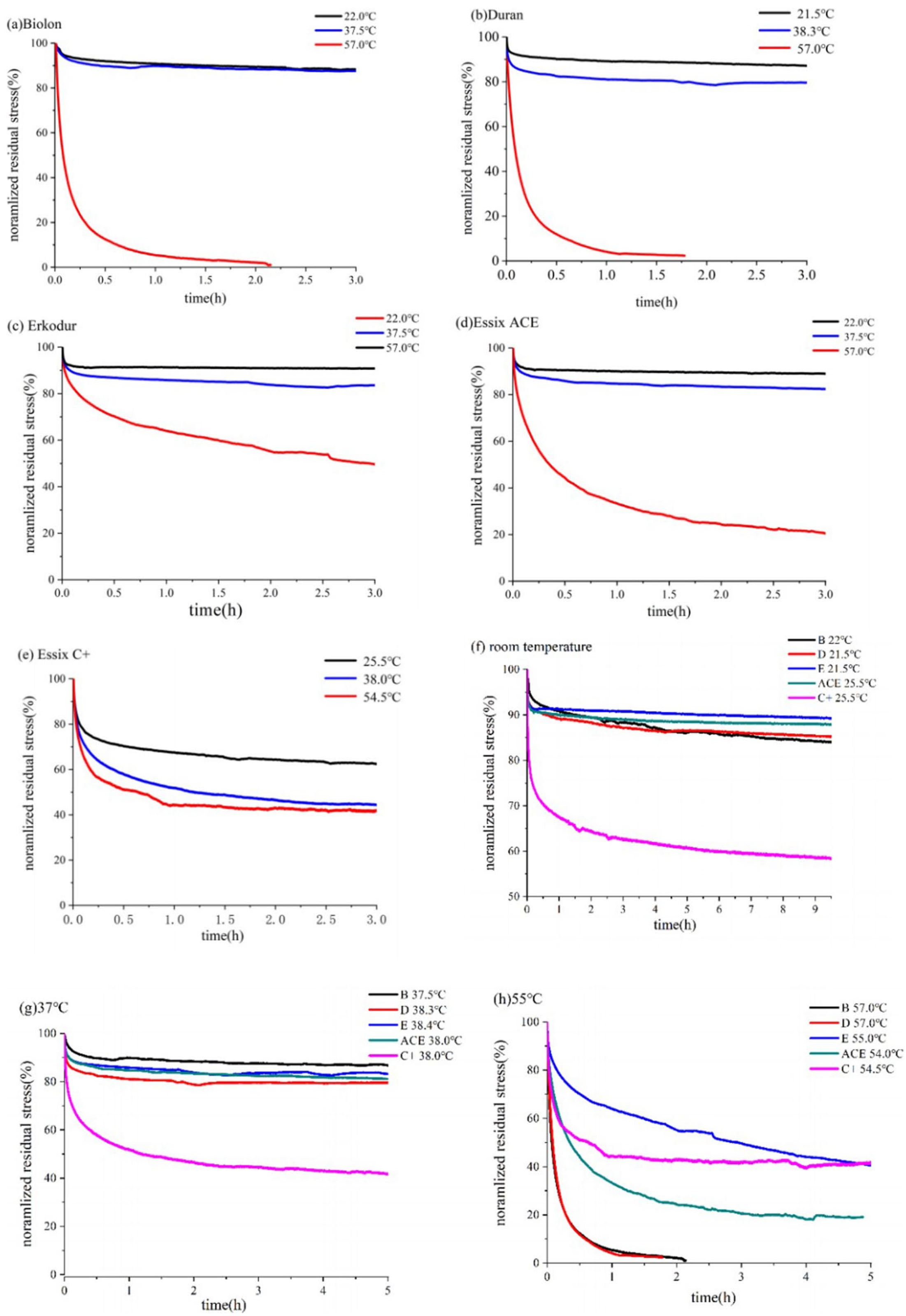

Fig. 3 Stress relaxation curve of the five tested materials under different temperature. Stress relaxation curve of Biolon (**a**). Stress relaxation curve of Duran (**b**). Stress relaxation curve of Erkodur (**c**). Stress relaxation curve of Essix ACE (**d**). Stress relaxation curve of Essix C+(**e**). Stress relaxation curve of the five materials in room temperature (**f**). Stress relaxation curve of the five materials at 37 °C (**g**). Stress relaxation curve of the five materials at 55°C (**h**)

Table 3 Summary of the residual stress after 3 h stress relaxation

temperature		Biolon	Duran	Erkodur	Essix ACE	Essix C+
room temperature	initial stress(MPa)	11.94 ± 0.74	12.72 ± 0.52	12.88 ± 1.28	11.33 ± 0.43	5.07 ± 2.08
	residual stress(MPa)	10.54 ± 0.48	11.08 ± 0.43	11.7 ± 0.75	10.08 ± 0.73	3.17 ± 1.22
	normalized residual stress(%)	88.31 ± 0.22	87.11 ± 0.17	90.81 ± 0.20	88.97 ± 0.42	62.55 ± 0.79
	decreasing rate(%)	11.69	12.89	9.19	11.03	37.45
37 °C	initial stress(MPa)	12.52 ± 0.43	11.55 ± 0.23	13.41 ± 0.56	11.55 ± 0.23	4.18 ± 0.76
	residual stress(MPa)	10.97 ± 0.66	9.19 ± 0.20	11.22 ± 0.38	9.52 ± 0.35	1.86 ± 0.99
	normalized residual stress(%)	87.56 ± 0.32	79.62 ± 0.47	83.58 ± 0.28	82.40 ± 0.31	44.44 ± 0.30
	decreasing rate(%)	12.39	20.38	16.32	17.6	55.56
55 °C	initial stress(MPa)	12.36 ± 0.63	12.49 ± 0.55	11.36 ± 1.23	10.71 ± 0.82	2.71 ± 1.76
	residual stress(MPa)	0	0	5.64 ± 0.75	2.2 ± 0.33	1.14 ± 0.82
	normalized residual stress(%)	0	0	49.61 ± 0.12	20.5 ± 0.61	42.01 ± 0.35
	decreasing rate(%)	100	100	50.39	79.5	57.99

The values are represented as the mean ± standard deviation, for their normal distribution

Normalized residual stress = residual stress/initial stress

Decreasing rate = 100 – final force/initial force × 100

five materials were greater than those at room temperature (22 °C) and ranged from 0.7% to 18.11% at 37 °C and from 20.54% to 88.31% at 55 °C. These findings confirmed that elevated intraoral temperature could accelerate the stress relaxation of orthodontic thermoplastic materials and highlighted the adverse impact of the frequent and prolonged consumption of hot beverages while wearing clear aligners, as such habits diminish orthodontic force.

We found that the residual stress of Biolon and Duran was greater than that of Erkodur; this trend was consistent with Fang's findings [8], but our values were approximately 30% greater. The difference was potentially attributed to the lower initial stress we applied, which ensured that the material remained in a linear elastic range. Some studies have indicated that the combined effects of multiple factors could accelerate material aging more than individual factors alone. Elkholy reported that continuous loading in water reduced strain faster than loading in an ambient environment [24]. Our modified temperature control system effectively isolated materials from direct contact with water, which could help reveal the effect of elevated temperature alone.

The stress relaxation behavior of materials with different chemical compositions was compared. We found that Biolon and Duran, both composed of PETG, displayed similar stress relaxation behaviors at different temperatures; these results indicated that the stress relaxation properties of orthodontic thermoplastics could be related to their chemical composition [9]. Erkodur (also PETG) exhibited distinct behavior, likely due to its different manufacturing processes. In addition, the polymers could be divided into two crystalline structures: amorphous structures and crystalline structures. Essix C + had a higher stress relaxation rate at both room temperature and 37 °C, which was likely attributed to its semicrystalline structure, whereas the other four materials had amorphous structures. In contrast, Ijima concluded that orthodontic forces delivered by CA were not likely influenced by their crystalline structure [10]. Since his research combined liquid and temperature, the difference likely originated from the water molecules penetrating the amorphous region or the crystalline fractions of the polymers and then changing their properties [25, 26].

With respect to the effect of wet environments, we found that deionized water had little effect on the stress relaxation of the four orthodontic thermoplastic materials and decelerated that of Essix ACE. Consistent with our results, Kwon reported that force delivery properties did not differ after thermocycling in deionized water [2]. Zhang reported that 37 °C deionized water immersion strengthened the mechanical properties of thermoplastic materials [27]. However, the intraoral environment could lead to calcification deposits, plaque formation [28], surface structure changes, and alterations in the local chemical composition [29] of orthodontic thermoplastic materials; moreover, we hypothesized that these changes would also affect their mechanical properties. Our results showed that artificial saliva had little effect on the stress relaxation of the tested materials. Whether artificial saliva had a different effect on other materials than deionized water

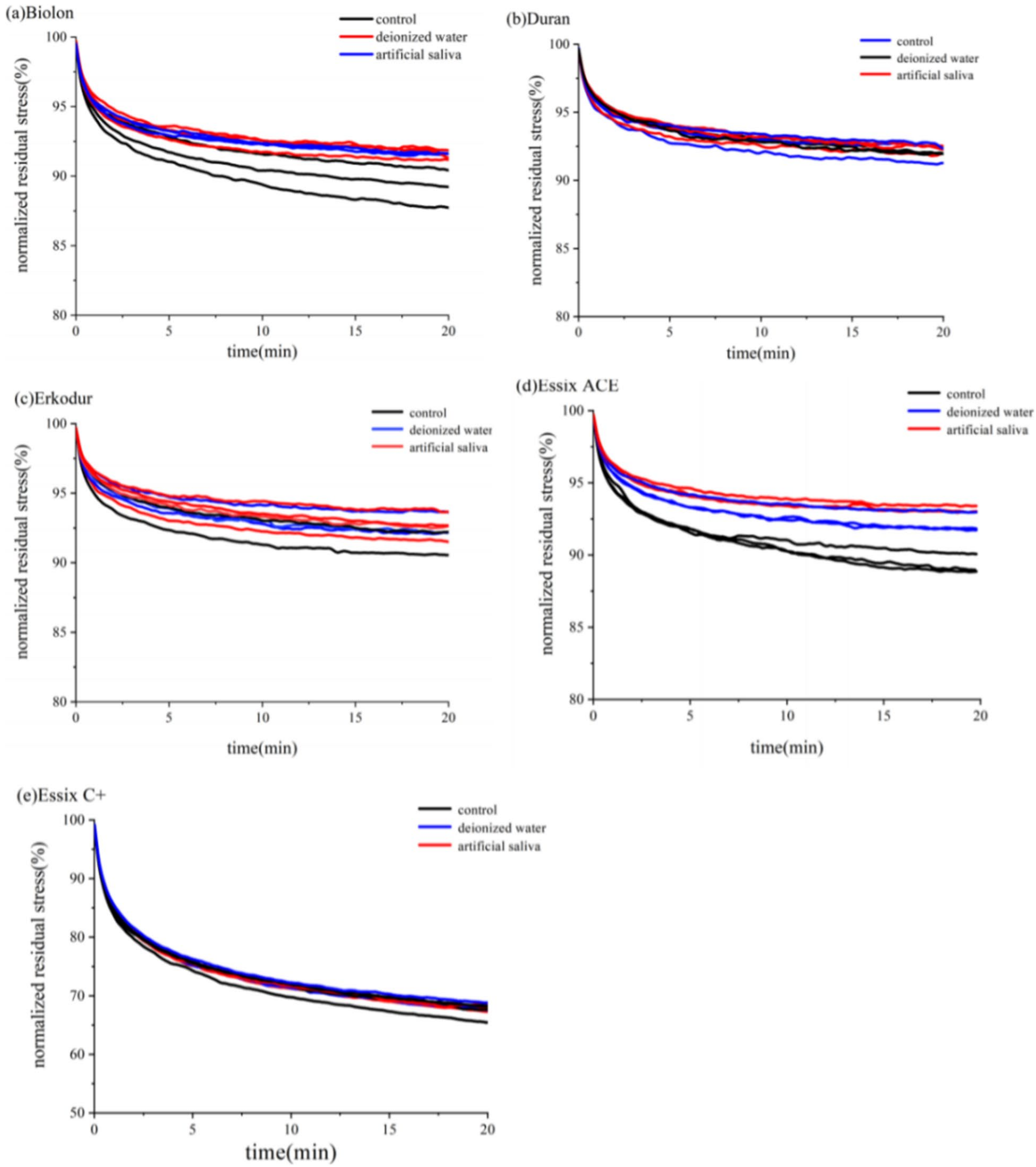

Fig. 4 Stress relaxation curve of the five tested materials under different wet environment (**a**-**e**). Stress relaxation curve of Biolon (**a**). Stress relaxation curve of Duran (**b**). Stress relaxation curve of Erkodur (**c**). Stress relaxation curve of Essix ACE (**d**). Stress relaxation curve of Essix C + (**e**)

needs further study. The above results indicated that the water component did not accelerate the aging of orthodontic thermoplastic materials and even retarded the aging of some materials and that the ionized components in saliva did not differ from those in deionized water.

Saliva pH value range from 6.2–7.6, and pH has different effects on materials with different chemical compositions. Alkas reported that the pH decreased to 5.5 after

Table 4 Residual stress of the five material after 2 weeks liquid immersion

normalized residual stress (%)	Biolon	Duran	Erkodur	Essix ACE	Essix C+
control	89.0 ± 1.4^{Aa}	91.9 ± 0.0^{Ab}	92.3 ± 0.3^{Ab}	89.3 ± 0.7^{Aa}	67.7 ± 0.3^{Ac}
deionized water	91.5 ± 0.1^{Aa}	91.9 ± 0.8^{Aa}	92.0 ± 1.6^{Aa}	92.2 ± 0.7^{Ba}	67.1 ± 1.6^{Ab}
artificial saliva	91.3 ± 0.4^{Aa}	92.2 ± 0.3^{Aab}	92.6 ± 1.2^{Aab}	93.1 ± 0.2^{Bb}	67.6 ± 0.5^{Ac}

The values are represented as the mean ± standard deviation, for their normal distribution

Normalized residual stress = residual stress/initial stress

Upper case (AB) represents column, lower case represents row(ab), same letter represents no significant difference among groups ($P > 0.05$)

coca cola was consumed and that the pH was restored by rinsing the mouth [30]. Pureprasert reported that the tensile strength of orthodontic elastic bands decreased after NaOH solution leaching [31]. Gao reported that the elastic modulus and nanohardness of dental resin-based composites were reduced in both acidic and alkaline environments [32]. Sorts of beverages and mouthwashes could also influence material properties by directly damaging physical material structures or indirectly changing the innate buffering ability of saliva. Qassar reported that 1% hydrogen peroxide (H2O2) reduced the force of orthodontic elastomeric chains [33] which could contribute to the oxidation or hydrogen degradation of copolymers [34]. The effects of saliva pH, beverages and mouthwashes on the aging process of thermoplastic aligner materials warrant further study.

In summary, by using a modified temperature-controlled water bath system, the effect of temperature as an isolated factor on the stress relaxation of orthodontic thermoplastic materials was revealed. The stress relaxation of the tested materials was accelerated by elevated temperatures, and that of Essix ACE and Erkodur showed comparatively less changes. The chemical composition and crystalline structure could influence the stress relaxation behavior of these materials. Two weeks of immersion in deionized water or artificial saliva had little effect on most of the tested materials but decelerated the stress relaxation of Essix ACE. Since the two factors were considered to occur simultaneously as hygrothermal environments, the wet environment could facilitate the accelerating effect of elevated temperature.

With respect to material aging, our findings indicated that Essix ACE and Erkodur were relatively superior candidates among the five tested commercial thermoplastic materials for clear aligner fabrication and orthodontic material modification [35].

From a clinical perspective, any behavior that can increase the intraoral temperature, such as hot beverages, hot food and smoking, should be avoided. In contrast, drinking normal-temperature beverages has no side effects. However, to conclude that the stress relaxation of thermoplastic aligner materials caused by elevated temperatures leads to orthodontic force decay to a clinically significant extent is illogical. The intraoral environment is complex and involves oral bacterial plaques and the pH mentioned above. The intraoral application of clear aligners is also complicated and involves various tooth movement patterns, various tooth movement distances per step, and periodic insertion and removal of aligners.

Several limitations exist in the present study. Clinically, raw materials are manufactured as clear aligners via a thermoforming process. The thermoforming process may influence the mechanical properties directly by changing the arrangement of internal molecular segments [36] or indirectly by decreasing the thickness [24, 37] and increasing the surface roughness of the material [1, 2]; these factors may also influence its stress relaxation behavior. As clear aligners are typically worn in the oral cavity for one to two weeks, further long-term observation is still needed. In addition, more commercial materials with different chemical compositions, such as thermoplastic polyurethane (TPU) and polycarbonate (PC), should be included.

Conclusion

The intraoral temperature accelerated the stress relaxation of the five tested commercial thermoplastic materials, and relatively small effects were observed for Erkodur and Essix ACE. Wet environments (deionized water and artificial saliva) had no accelerating effect on the four orthodontic thermoplastic materials but had a decelerating effect on the Essix ACE.

Abbreviations

CA Clear aligner
PETG Polyethylene terephthalate glycol
PP Polypropylene
PE Polyethylene

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13005-025-00497-7.

Supplementary Material 1: Fig. 1: Specimens incubated in a ziplock bag full of liquid, with no testing parts overlapping, and no bubbles on the surfaces of testing parts

Supplementary Material 2: Fig. 2: Preliminary uniaxial tensile test. (a) a dumbbell-shaped specimen. (b) Specimen loaded with a universal testing machine in the uniaxial tensile test. (c) Stress–strain curve of the tensile test of the five tested materials in standard environment. The peak point refers to the ultimate tensile stress and strain

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Not applicable.

Authors' contributions
X.Y.C. and F.R.L. contribute equally to this work. X.Y.C. contributed to material testing, data analysis and manuscript writing. F.R.L. contributed to conceptualization, experiment designing, material testing, and data analysis. J.J.H. contributed to conceptualization, writing- review& editing and supervision.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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