The Effect of Thermal Cycles on Mechanical Properties of 3D-Printed Dental Aligners Incorporating Long Optical Glass Fibers

Introduction

The global shift towards **aesthetic dentistry** has made **clear aligners** a preferred choice over traditional braces. However, **3D-printed** aligners face challenges such as **mechanical deformation, staining, and loss of strength** over time, compromising treatment efficacy. This project addresses these limitations by innovating a **composite material (TC-85)** that embeds **long optical glass fibers** into 3D-printed resin aligners. We tested this novel material under simulated oral conditions to evaluate its potential for clinical use.

Research Aim

- Develop and compare **3D-printed TC-85 resin specimens** with/without glass fiber reinforcement
- Simulate **clinical aging** through **thermocycling**
- Quantify changes in the **mechanical properties and optical performance** of **color change, tensile strength, elastic modulus, and surface roughness.**

Materials and Methods

Specimen Preparation

- Material: **TC-85 biocompatible dental resin**
- Reinforcement: **Polyimide-coated optical glass fibers** (156 µm diameter)
- Design: **Dumbbell-shaped specimens** compliant with ISO 527-1:2019

Specimens were 3D-printed using Phrozen Sonic Mini 8K printer, with manual fiber embedding during printing. Process then followed with post-processing included UV curing.

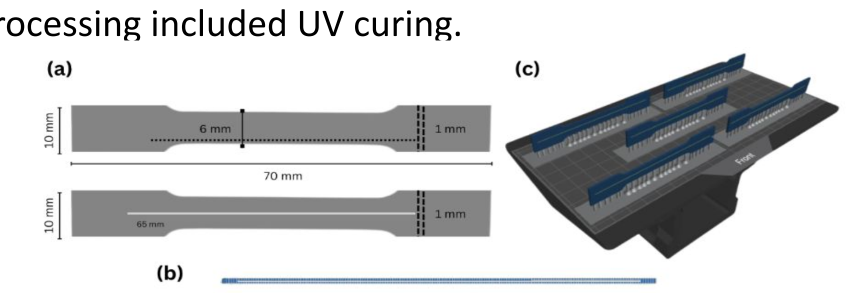


Figure 1 (a) Dumbbell Shape Specimen Dimensions. (b) Rectangular Cavity for Embedding Fiber. (c) 3D-Printing Layout in Chitubox_Basix. with Support

Experimental Protocol

- Divided into three subgroups for the thermal cycling procedure
- **Thermocycling of 5°C ⇄ 55°C with 20s dwell time to simulating 7–14 days of clinical use**

Table 1 Experimental Group Distribution of 30 Printed Specimens

Group	Type of Specimens
Control (10 Specimens)	Fiber-Reinforced - 5 specimens without thermocycle Non-Reinforced - 5 specimens without thermocycle
500 Cycle (10 Specimens)	Fiber-Reinforced - 5 specimens 500 thermocycle Non-Reinforced - 5 specimens 500 thermocycle
1000 Cycle (10 Specimens)	Fiber-Reinforced - 5 specimens 1000 thermocycle Non-Reinforced - 5 specimens 1000 thermocycle

Testing Procedure

- *Color:* Nix Pro 2 sensor to conduct **ΔE calculation** via **CIELAB** values

$$\Delta E^* = \sqrt{\Delta L^*2 + \Delta a^*2 + \Delta b^*2}$$

- *Tensile:* Instron ElectroPuls E3000 with crosshead speed of **5 mm/min**

$$\sigma = \frac{F}{A_0} \qquad \epsilon = \frac{\Delta L}{L_0}$$

- *Surface Roughness:* Atomic Force Microscopy of **10x10 µm²**

Result

Fiber Reinforcement Significantly Enhances Mechanical Properties

- *Elastic Modulus:* Reinforcement resulted in a **2.6-3x increase in stiffness**. This profound improvement was consistent across all thermocycling groups, highlighting the fiber's role as the primary load-bearing component.

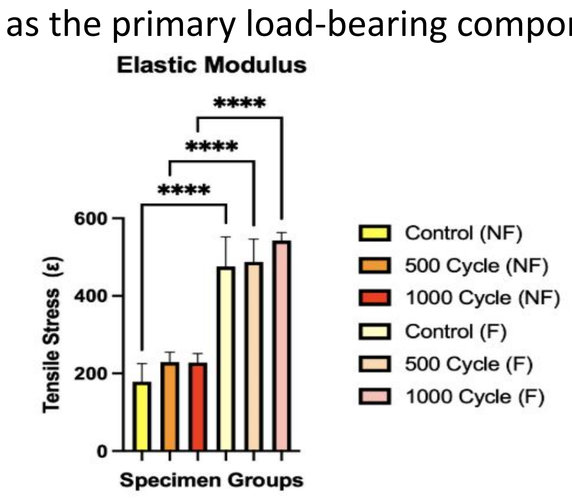


Figure 2. Interleaved Bars of Mean with SD for Elastic Modulus from UTS

- *Ultimate Tensile Strength:* Fiber-reinforced specimens demonstrated a **42-48% increase in UTS** across all aging conditions compared to non-reinforced controls ($p < 0.0001$). Thermal cycling showed minimal impact on UTS.

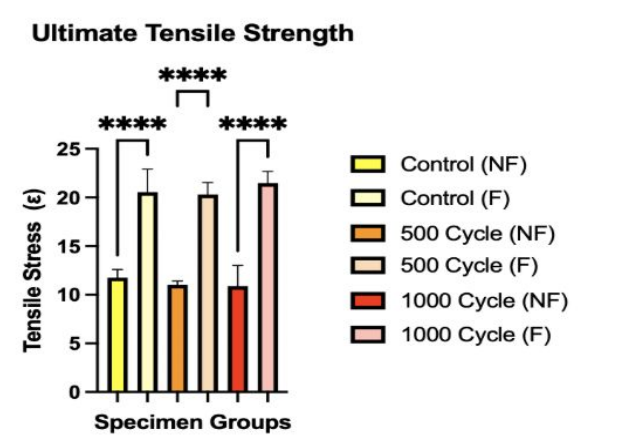


Figure 3. Interleaved Bars of Mean with SD for UTS

Induces Surface Degradation but Minimal Mechanical Loss

- *Color Change (ΔE):* A complex, **non-linear trend** in color change was observed. The most significant discoloration occurred within the first 500 cycles. Fiber-reinforced specimens exhibited a slower rate of change, suggesting a potential mitigating effect.

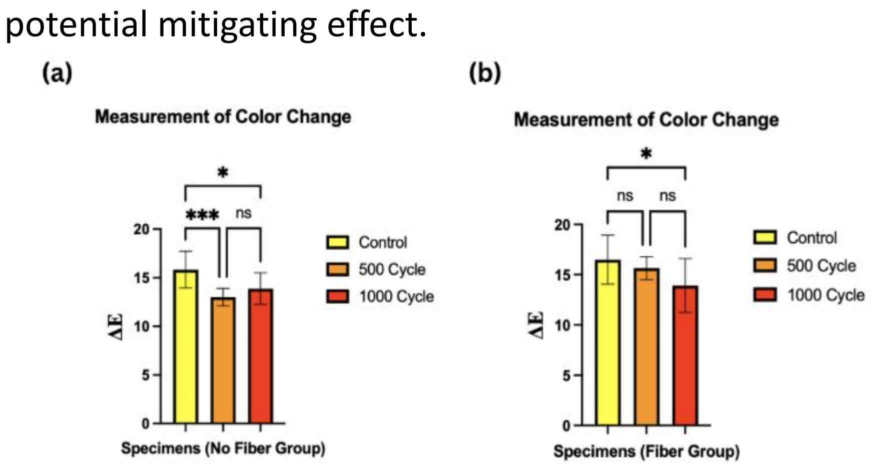


Figure 5. (a) Interleaved Bars of Mean with SD for Color Change in No Fiber Groups **(b)** Interleaved Bars of Mean with SD for Color Change in Fiber Groups

- *Surface Roughness:* AFM revealed a **significant increase in surface roughness (Ra)** after thermocycling ($p < 0.0001$), with values nearly doubling after 500 cycles. Roughness plateaued between 500 and 1000 cycles, suggesting most degradation occurs early.

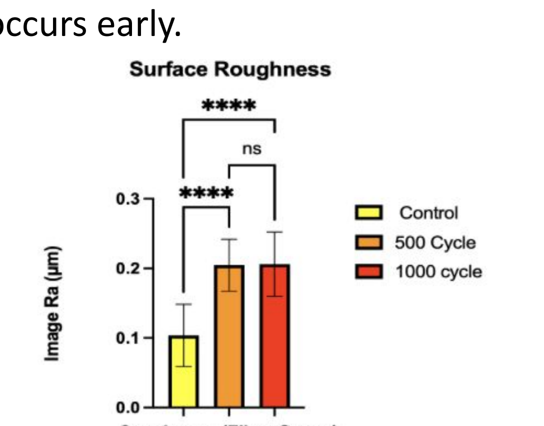


Figure 4. Interleaved Bars of Mean with SD for Surface Roughness Image R_a from AFM

Figure 5a. 2D AFM Image

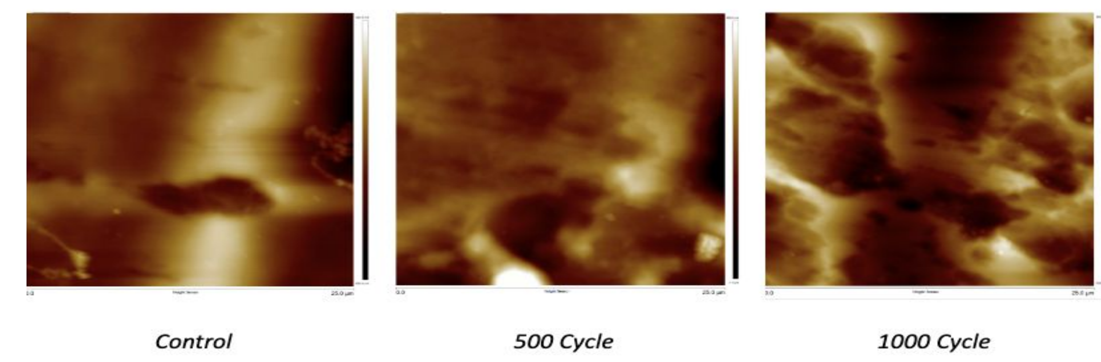
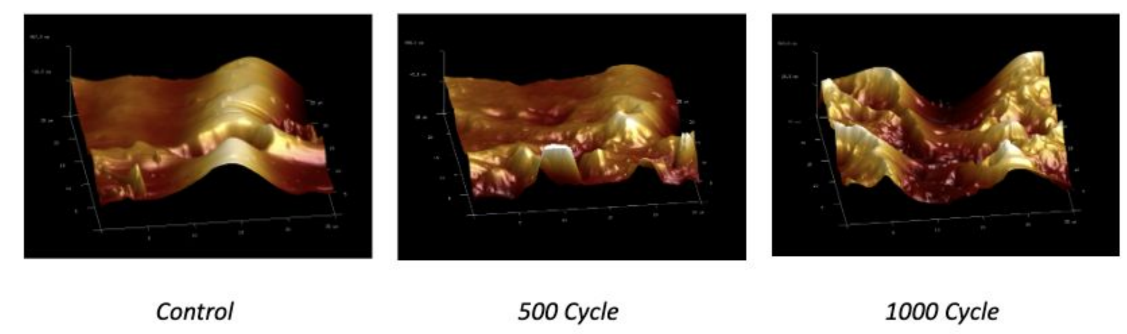


Figure 5b. 3D AFM Image



Discussion

Color Change (ΔE)

- An unexpected **decrease in discoloration** was observed after thermal cycling. This may result from a **stabilization effect**, where cycling **reduces surface irregularities** and **residual monomers**, improving optical clarity. Both fiber and non-fiber groups followed this trend, indicating color stability is highly dependent on **resin formulation** and **cycling protocol**.

Surface Roughness (Ra)

- Thermal cycling significantly **increased surface roughness**. However, minimal change was noted between 500 and 1000 cycles, suggesting a **plateau effect** where initial damage does not progressively worsen with cycling.

Elastic Modulus

- Fiber reinforcement significantly **increased stiffness**. Thermal cycling somehow increased the modulus in all groups which may due to a **post-curing effect** that enhances cross-linking.

Ultimate Tensile Strength

- Fiber specimens showed superior UTS suggests improved **fiber-matrix bonding and stress relief**. Non-fiber specimens is declining due to microcrack formation from repeated stress.

Limitations

- Limited sample size (n=5/group)
- Thermal cycling may not fully simulate long-term clinical use
- Potential for material variability inherent in 3D-printing

Conclusion

Fiber reinforcement **enhances key mechanical properties** of 3D-printed aligners. Thermal cycling **triggers complex physical and chemical changes**, improving some properties through post-curing while degrading others through surface wear. **Further research** with larger samples and longer cycling is needed to validate these findings for clinical application.

Acknowledgement

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