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Effect of the alkaline surface modification of the substrate fabric on the peel strength of 3D printed composite fabrics

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Abstract

In the modern fashion industry, 3D printing technologies are increasingly combined with traditional textile fabrics to create innovative 3D garments. Although this integration may not entirely replace traditional clothing manufacturing techniques, it presents opportunities for innovative applications in garment production. In terms of the performance of 3D printed composite fabrics (3D-PCF), adhesion between the 3D printing polymer and the substrate fabric is crucial. However, research on how fabric surface properties influence the adhesion between the substrate fabric and 3D filaments remains limited. Therefore, this study investigates the effects of alkaline surface modifications on the peel strength of substrate fabrics bonded with 3D printing filaments. Alkaline treatment reduces fabric weight, thickness, and tensile strength. Moreover, as both alkaline treatment time and temperature increased, the 3D-PCF peel strength decreased by 30–50%. This is attributed to the reduced fiber diameter and smaller adhesive surface area. Conversely, at NaOH concentrations of 4% and 6%, the increased surface roughness improved peel strength, reaching 15.6 N and 15.9 N, respectively. However, at 8%, surface etching reduced peel strength to 3.7 N. These results demonstrate that optimal alkaline treatment improves surface roughness and the peel strength, while excessive treatment diminishes the adhesive surface area and adhesion strength. Excessive treatment also significantly alters bulk fabric properties, further reducing adhesion. Controlling alkaline concentration to limit bulk changes while increasing surface roughness is an effective strategy to improve 3D-PCF adhesion. Enhanced peel strength through surface modification is expected to prolong the lifespan of 3D-PCF, especially in high-performance applications.

Keywords: 3D printing, 3D printing composite fabric, Surface modification, Alkaline treatment, Peel strength

Introduction

The integration of 3D printing technologies with traditional textile fabrics has revolutionized the fashion industry, enabling the creation of innovative 3D garments. Although this approach may not entirely replace conventional garment manufacturing methods, it offers unprecedented opportunities for design and functionality.

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Fused deposition modeling (FDM), a widely used 3D printing method, involves depositing molten thermoplastic polymer filaments through a nozzle to construct three-dimensional structures (Eutionnat-Diffo et al., 2020; Korger et al., 2016). 3D-printed composite fabrics (3D-PCF) produced via FDM retain the tensile strength and flexibility of conventional fabrics while allowing for intricate 3D shapes and decorative geometric structures (Kechagias et al., 2024; Sitotaw et al., 2020; Yap & Yeong, 2014). For the commercialization of 3D-PCF, the stable adhesion between the substrate fabric and the 3D printing filament is essential, as they directly impact the durability of the composite fabric (Narula et al., 2018).

Research on the adhesion of 3D-PCF has primarily focused on how 3D printing parameters and fabric properties affect adhesion. For instance, in the FDM process, the distance between the nozzle and the printing bed (z-distance) is critical. A shorter z-distance enhances adhesion by pressing the polymer more firmly into the fabric's pores (Spahiu et al., 2018). Similarly, increasing the print bed and extruder temperatures is essential, as higher temperatures reduce filament viscosity, allowing deeper penetration into the fabric, which improves adhesion (Cheung & Choi, 2023; Spahiu et al., 2018). Various fabric characteristics also influence adhesion strength, including fiber composition (Demir & Seki, 2023; Korger et al., 2020), yarn type (Meyer, 2019), yarn thickness (Silvestre et al., 2023), fabric density (Eutionnat-Diffo et al., 2020; Mpofu et al., 2019), fabric thickness (Korger et al., 2016; Mpofu et al., 2019; Störmer et al., 2021), and fabric structure (Eutionnat-Diffo et al., 2019; Sanatgar et al., 2017). Notably, it has been reported that polarity interactions between the 3D printing filament and the fabric have a greater effect on adhesion strength than the chemical composition of the fibers themselves. In terms of yarn type, staple fiber fabrics, which contain protruding fibers, exhibit stronger mechanical interlocking with the filament and thus higher adhesion compared to filament yarn fabrics. As yarn thickness increases, the spacing between yarns widens, allowing the filament to penetrate more easily and expanding the contact area, which in turn enhances adhesion. In contrast, higher fabric density increases the cover factor and reduces pore size, thereby limiting filament penetration and lowering adhesion. Fabric thickness is also closely related to adhesion; thicker fabrics provide a larger contact area, resulting in stronger bonding. Lastly, knitted fabrics exhibit superior adhesion performance compared to woven fabrics due to their inherently porous structure, which facilitates better filament infiltration and anchoring. These factors play a critical role in determining adhesion between the 3D printing filament and the substrate fabric, directly affecting the performance and durability of the composite fabric.

To improve the adhesion between the substrate fabric and the 3D printing filament, increasing the fabric's surface roughness and wettability is necessary. Moreover, enhanced interaction between the adhesive and substrate molecules is essential (Molina et al., 2010). Surface modification methods are primarily employed to improve adhesion between the substrate fabric and polymer. By making the fabric surface more hydrophilic through surface modification, the adhesion can be enhanced.

Alkaline hydrolysis is widely used in the fashion industry to improve the wettability, dyeability, texture, and gloss of polyester (PET) fabrics (Oh & Park, 2018). This process uses hydroxyl ions (OH^-) from a sodium hydroxide (NaOH) solution to attack the electron-deficient carbonyl carbon (C=O) within polyester molecular structures. This

reaction cleaves molecular chains, forming new terminal groups such as hydroxyl (–OH) and carboxylate ($–COO^-$). These changes primarily occur on the fiber surface, altering its chemical and physical properties (Youn & Park, 2019). Furthermore, the alkaline treatment creates nanoscale roughness on the fiber surface, enhancing its surface texture. Compared to methods like plasma etching, alkaline hydrolysis is more economical and practical, making it suitable for mass production (Oh & Park, 2018; Youn & Park, 2019). Surface modification is expected to improve the surface roughness and wettability of fabrics, enhancing the adhesion of the 3D-PCF.

Previous studies on 3D-PCF adhesion have predominantly focused on the effects of 3D printing processes and fabric properties. However, research that strategically addresses interfacial adhesion enhancement through surface treatment remains limited. In particular, few studies have quantitatively analyzed how chemical and structural modifications of the fabric surface influence adhesion mechanisms. This indicates the need for more diverse and systematic surface modification approaches, along with verification of their effects, to ensure the functionality and durability of 3D-PCF. Accordingly, this study aims to analyze the adhesion characteristics between the substrate fabric and 3D printing filament in 3D-PCF produced using the FDM process. The research focuses on the effects of alkaline surface treatment, in which polyethylene terephthalate (PET) fabrics are subjected to alkaline hydrolysis. The resulting surface changes are quantitatively evaluated in relation to peel strength.

Through this investigation, the study seeks to experimentally verify whether surface modification via alkaline hydrolysis affects interfacial adhesion in 3D printing. Furthermore, by highlighting the potential of surface modification to enhance adhesion performance beyond what can be achieved through printing condition adjustments alone, the study aims to contribute to a deeper understanding of interfacial design in 3D-PCF.

Methods

Materials

3D printing filament

Table 1 shows the characteristics of the 3D printing thermoplastic polyurethane (TPU) filament (eLastic 3D filament, ESUN, Korea). The listed properties are based on the manufacturer's specifications. TPU is known for its excellent flexibility and durability, making it easy to deform and recover. These properties make TPU widely used in 3D printing applications such as wearable devices and functional textiles.

Table 1 Properties of the TPU

Property	Value
Elongation at break (%)	500
Tensile strength (N)	228.6 ± 4.8
Diameter (mm)	1.75
Tensile modulus (MPa)	52
Extruder temperature range (℃)	210–230
Density (g/cm^3)	1.12
Shore hardness	85 A

Table 2 Characteristics of the substrate fabric

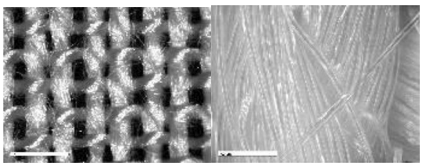
Specification	Description
Fiber composition	PET 100%
Yarn type	Spun yarn
Fabric structure	Plain weave
Weight (g/m^2)	141.1
Thickness (mm)	0.31
Fabric density (counts/5cm)	53 × 51
Fiber diameter (μm)	11.9
Images	
	× 100 (scale bar: 1 mm) × 1000 (scale bar: 100 μm)

Table 3 Alkali treatment conditions

Temperature (℃)	Time (min)	NaOH aqueous solution concentration (%)
70, 80	30, 60, 90	4, 6, 8

Substrate fabric

The substrate fabric refers to the material used as the base layer for 3D printing filament during 3D-PCF production. PET fabric was selected to evaluate the effects of surface modification on the peel strength of 3D-PCF. Table 2 presents the characteristics of the PET fabric.

Surface modification of the substrate fabric by alkaline treatment

The alkaline treatment conditions presented in Table 3 were established to clearly distinguish between conditions that induce changes only on the PET fabric surface and those affecting the internal bulk properties of the fibers. These conditions were established to systematic analysis how structural modifications influence the peel strength of 3D-PCF. Specifically, based on previous research (Han et al., 2016), two treatment temperatures (70 °C and 80 °C) and three treatment durations (30, 60, and 90 min) were selected to effectively control the activation level and penetration depth of the NaOH solution. Additionally, the NaOH concentrations were set at 4%, 6%, and 8% to induce varying degrees of hydrolysis, ranging from mild surface etching to more extensive structural changes from the fiber surface to the core. For the temperature and time variation test, an 8% NaOH solution was used.

PET fabric samples (20 cm × 20 cm) were immersed in the solution at 70 °C and 80 °C for 30, 60, and 90 min, respectively. To examine the effect of NaOH

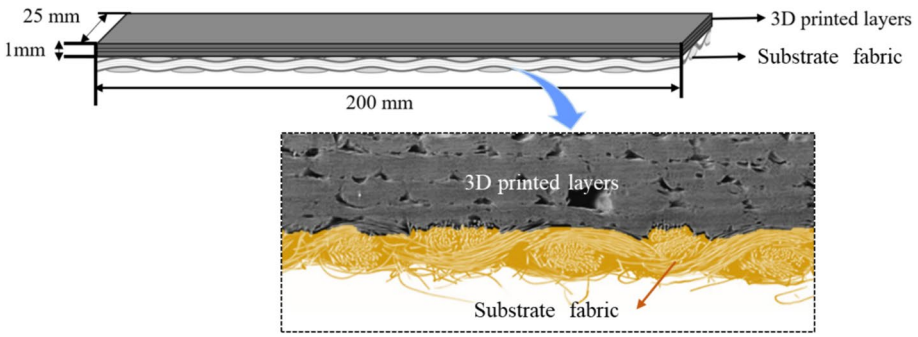


Fig. 1 3D-PCF structure (200 mm × 25 mm × 1 mm)

Table 4 3D printing conditions

Condition	Value
Temperature of nozzle (℃)	240
Temperature of the heating bed (℃)	60
Printing speed (mm/s)	30
Infill (%)	20
z-distance (z-offset)	300

concentration, 4%, 6%, and 8% NaOH solutions were prepared, and PET fabric samples were treated at 70 °C for 30 min in each concentration.

After alkaline treatment, the fabric was rinsed with distilled water until the pH reached 7 and then air-dried at room temperature. We calculated the weight loss of treated fabrics by measuring sample weights five times before and after treatment, using Eq. (1).

$$\text{Weight loss rate (\%)} = \frac{W_1 - W_2}{W} \times 100 \tag{1}$$

W_1: Weight of the sample before alkaline treatment.

W_2: Weight of the sample after alkaline treatment.

3D printing process

The 3D printer used for this study was the STYLE NEO-A31C (Cubicon, Korea). A 300 mm × 300 mm fabric was placed on the heating bed, and a 3D model, designed in Rhinoceros CAD software with dimensions of 200 mm × 25 mm × 1 mm (length × width × height), was printed onto it (Fig. 1). The printed sample had a rectangular shape, and the filament was deposited layer by layer in alternating horizontal and vertical directions according to the model geometry.

Table 4 provides the 3D printing conditions. The nozzle temperature used was 240 °C, which slightly exceeds the manufacturer's recommended extrusion temperature range for TPU (210–230 °C). However, preliminary tests showed that at this higher temperature, the extrusion stability of the filament and its adhesion to the fabric improved, and thus this condition was selected. The z-distance, which represents the distance between the nozzle and the heating bed, was determined based on fabric thickness. The z-offset (distance between the nozzle and the fabric) was initially set to 10 for a fabric thickness

of 0.01 mm and adjusted in increments of 10 for thicker fabrics. To identify the minimum distance at which the 3D filament could be extruded onto the fabric, the z-offset was gradually reduced. For example, for a fabric thickness of 0.31 mm, the initial z-offset was set to 310 and was incrementally decreased by 10 until the optimal distance was identified. The final z-distance was set to 300.

Characterization

Morphology and fiber diameter

Surface morphology was analyzed using a focused ion beam-scanning electron microscope (FIB-SEM, Carl Zeiss, Germany). During the analysis, fiber diameter was measured at five distinct points per sample, and the average value was calculated.

Weight and thickness

The weight(g/m^2) was calculated in accordance with ISO 3801:1977 (International Organization for Standardization [ISO], 1977). Fabric samples measuring 100 mm × 100 mm were weighed five times using an electronic balance (WBA-320, Daihan Scientific Group, Korea). Thickness was measured following ISO 5084:1996 using a thickness gauge (Hanwon Testing Co., Korea), with the average calculated from measurements at five different points(ISO, 1996).

Surface roughness

The surface roughness was evaluated following ISO 4287:1997, using a Confocal Laser Scanning Microscope (LMS 900, Carl Zeiss, Germany) (ISO, 1997). The measurement area was set to 0.6 mm × 0.6 mm, and the average roughness (R_a) was calculated. Measurements were taken from warp and weft directions at five locations, avoiding pores of the fabric (Fig. 2). The final average roughness (μm) was calculated based on repeated measurements at five locations.

Water contact angle

We assessed wettability changes after surface treatment by measuring static water contact angles with a water contact angle measurement device (SmartDrop Plus_HS, Femtobiomed, Korea). The fabric was fixed on a glass slide, and a 10 μL water droplet was applied to its surface. Measurements were recorded at 1, 10, and 20 s. The final

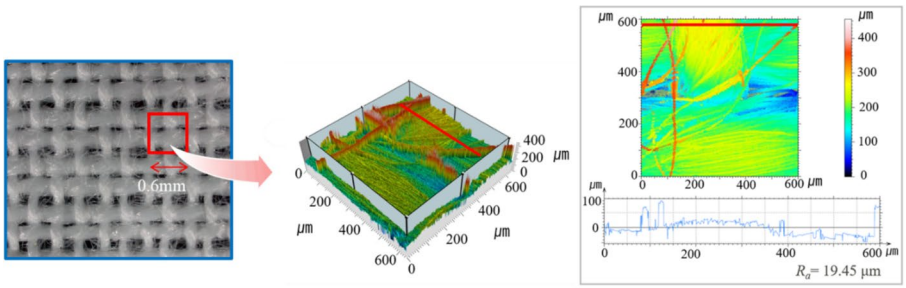


Fig. 2 Roughness measurement

penetration time for the droplet was observed for 30 s. Each sample was tested at three positions, and the average value was used.

Peel strength

Since no standard exists for measuring the adhesion between substrate fabric and 3D printing filament, the peel strength of the 3D composite fabric was measured according to ISO 11339:2022 using a universal testing machine (5982 Series, Instron, USA) (ISO, 2022). The sample was positioned between upper and lower clamps (Fig. 3). The lower clamp held the substrate fabric, while the upper clamp secured the TPU printed on the fabric. The upper clamp moved at a speed of 100 mm/min. This process was repeated five times, and the average peel strength was calculated.

Tensile strength

To evaluate the effect of alkaline treatment on the strength of the PET fabric, tensile strength was measured in the warp direction using a universal testing machine (5982 Series, Instron, USA). We set the tensile speed to 100 mm/min, with a grip-to-grip distance of 200 mm. We tested each condition five times, and the average maximum load values were recorded as the tensile strength results.

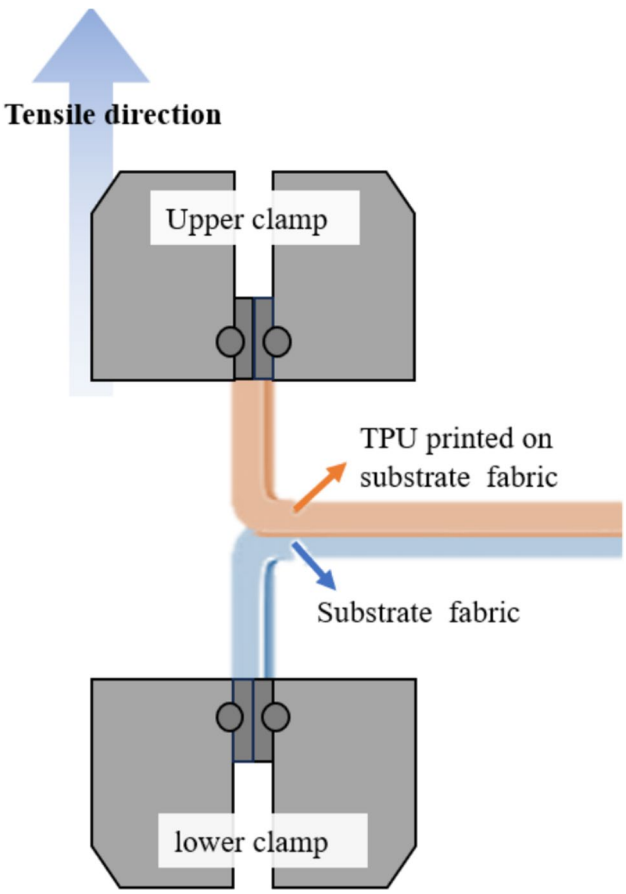


Fig. 3 Peel strength measurement

Results and Discussion

Changes in the fiber surface and diameter by alkaline treatment

Tables 5 and 6 presents the changes in fiber surface morphology and diameter of PET fabric treated with an 8% alkaline solution under varying temperatures (70 °C and 80 °C) and times (30 min, 60 min, and 90 min). The untreated fabric exhibited a smooth surface. However, as alkaline treatment temperature and duration increased, etching occurred, resulting in surface roughness. Higher temperatures intensified molecular activity, and prolonged exposure to hydroxyl ions led to increased etching and the development of roughness. The sample treated at 80 °C for 90 min showed more pronounced roughness on the fiber surface compared to the other samples. The fiber diameter decreased by

Table 5 SEM images of alkaline hydrolyzed PET under different time and temperature at 8% concentration

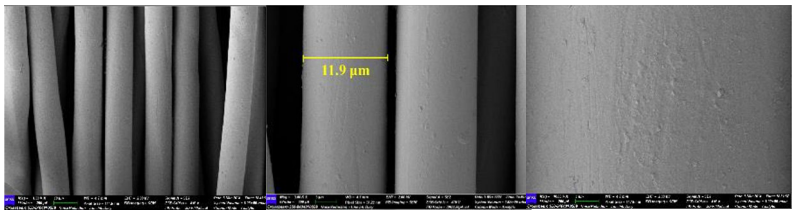
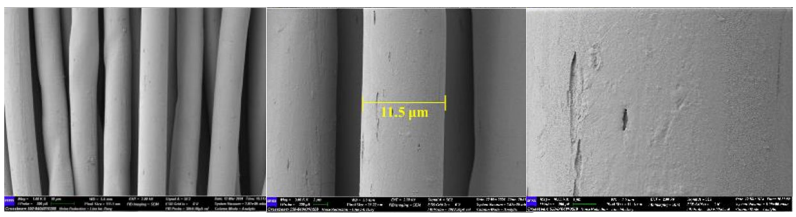
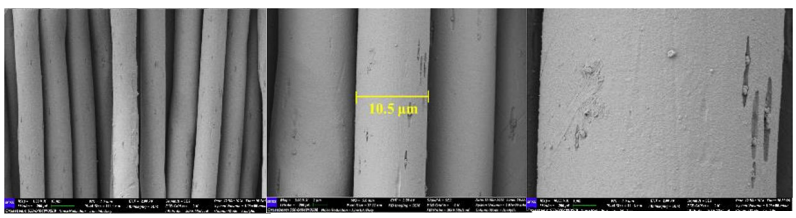
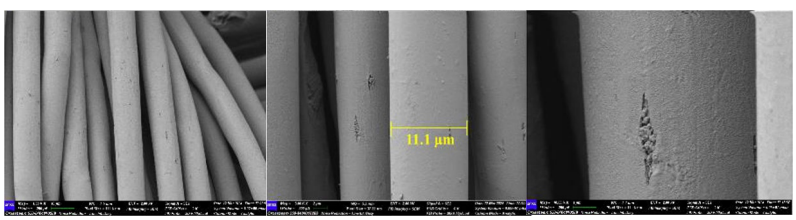
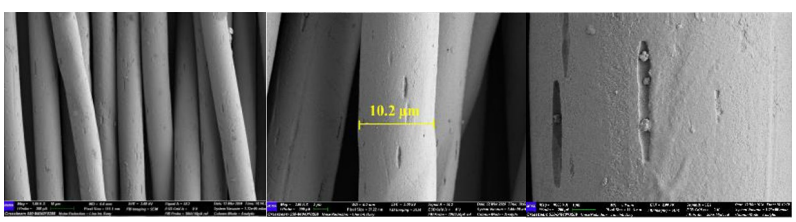
		Magnification		
Conditions		**×1000**	**×3000**	**×10,000**
Untreated				
70℃	30 min			
	90 min			
80℃	30 min			
	90 min			

Table 6 Diameter changes of alkaline hydrolyzed PET under different time and temperature at 8% concentration

Conditions	Diameter (μm)
Untreated	11.9
70℃	
30 min	11.5
90 min	10.5
80℃	
30 min	11.1
90 min	10.2

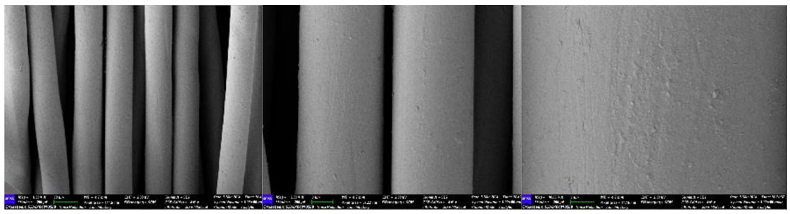
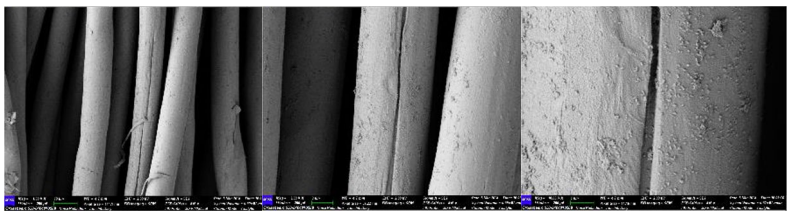
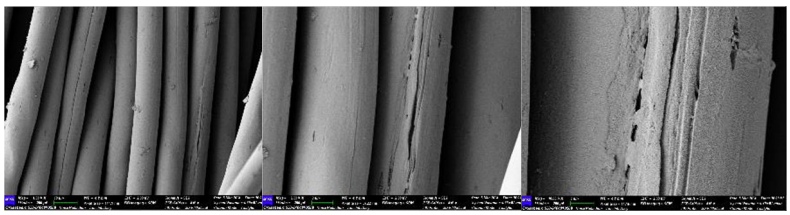
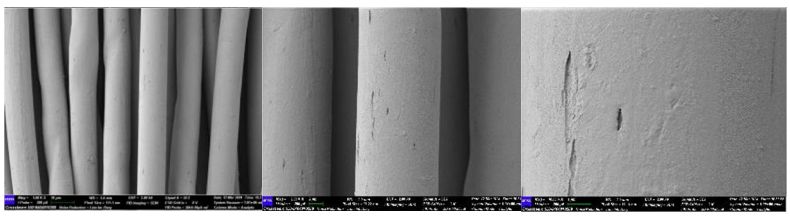
about 14% in the sample treated at 80 °C for 90 min (10.2 μm) compared to the untreated sample (11.9 μm). This decrease in the fiber diameter can be interpreted as a result of etching on the fiber surface.

Table 7 highlights the morphology of PET fabric treated with sodium hydroxide (NaOH) solutions of varying concentrations (4%, 6%, and 8%) at 70 °C for 30 min. As the NaOH concentration increased, surface etching formed micro-craters and roughness. Samples treated with 4% and 6% NaOH exhibited finer etching characterized by bumps or nano-craters, rather than prominent micro-craters observed at higher concentrations.

Changes in fabric weight and thickness by alkaline treatment

Figure 4a illustrates the changes in fabric weight and thickness after alkaline treatment using an 8% NaOH solution under different temperatures and times. The untreated fabric's weight was 528.1 g/m^2, and the weight of the sample treated at 70 °C for 90 min decreased to 468.1 g/m^2 (a 13% reduction.) At 80 °C for 90 min, the weight further declined to 458.3 g/m^2, a 15% decrease compared to the untreated fabric. The thickness of the untreated fabric was 0.31 mm, and the sample treated at 70 °C for 90 min had a thickness of 0.30 mm, showing a reduction of about 4%. At 80 °C, the thickness of the sample treated for 90 min decreased to 0.28 mm (a 9% reduction). These changes are consistent with the mechanism of alkaline treatment, wherein when temperature increased and treatment time increased, both the weight and thickness decreased. This is related to the alkaline treatment mechanism, wherein the PET fabric undergoes hydrolysis with alkali, and the ester bonds are broken. The resulting low-molecular-weight substances are detached from the surface, which reduces the weight (Han et al., 2016). Additionally, as temperature increases, the relative activity of the hydroxyl anion increases, increasing reaction efficiency. Longer treatment times mean more frequent reactions, likely contributing to a higher weight reduction rate. Moreover, the fiber thickness also decreases as the fiber material is removed because of surface etching. When treated at higher temperatures for longer times, the fiber surface area increased. This provides a larger reaction area with hydroxyl ions. This accelerates the diffusion of the alkaline solution into the fiber, resulting in thickness reduction. However, the reason the rate of weight reduction does not correlate with thickness changes is that etching occurs primarily on the surface fibers, so overall weight loss and fabric thickness reduction do not occur in the same proportion.

Table 7 SEM images of alkaline-hydrolyzed PET under different concentrations (at 70℃ for 30 min)

	Magnification		
Concentration (%)	**×1000**	**×3000**	**×10,000**
Untreated			
4			
6			
8			

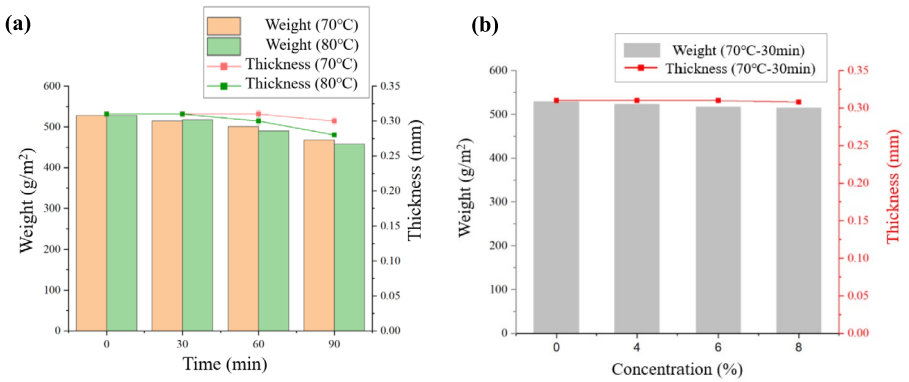


Fig. 4 Changes in the thickness and weight of the PET fabrics **a** with different temperatures and times under 8% NaOH concentration and **b** with different NaOH solution concentrations at 70 °C for 30 min

Figure 4b illustrates the changes in the weight and thickness of PET fabric as a function of NaOH solution concentration. The sample treated with a 4% NaOH solution weighed 523.1 g/m^2, showing a 1% reduction. The sample exposed to a 6% NaOH solution weighed 516.7 g/m^2, reflecting a 2% decrease, while the sample treated with 8% NaOH solution weighed 514.8 g/m^2, indicating another 2% reduction. For NaOH concentrations below 8%, the sample's weight change was not significant. When measuring the thickness of the PET fabric treated with varying NaOH solution concentrations, the samples treated with 4%, 6%, and 8% NaOH solutions all had a thickness of 0.31 mm. This represented a decrease of about 1% to 2% compared to untreated samples. Similar to the weight reduction, the effect on the thickness was minimal.

Changes in the surface roughness by alkaline treatment

Figure 5a reflects the changes in the surface roughness (R_a) because of the surface etching depending on the alkaline treatment temperature and time. As the duration of the alkaline treatment time increased, surface roughness (R_a) value showed a slight increase. Compared to the untreated sample with an R_a value of 13.1 μm, the values increased to 15.2 μm (approximately 16%) at 70 °C and 15.4 μm (approximately 17%) at 80 °C. This indicates that the etching of the fiber surface during the treatment formed roughness and influenced the increase in the surface roughness.

Figure 5b reflects the changes in the surface roughness of the PET fabric depending on the concentration of the NaOH solution. As alkaline concentration increased, overall surface roughness also increased. Compared to the untreated fabric (13.1 μm), the samples treated with 4% NaOH solutions showed an increase in R_a to 23.51 μm, representing up to a 78% increase. This heightened roughness stemmed from nano-crater formations observed on the surfaces of samples treated with 4% and 6% solutions. In this stage, the balance between etching kinetics and solution diffusion activates the amorphous–crystalline interfaces to generate high-density asperities, and some oligomers redeposit on the fiber surface as aggregates (Gupta et al., 2014). However, when treated with 8% NaOH, the PET fiber surfaces underwent more extensive etching, eliminating fine nano-roughness and resulting in smoother surfaces compared to those treated with lower concentrations. Consequently, roughness values decreased at this concentration. This occurs because etching proceeds excessively, causing adjacent craters to merge and

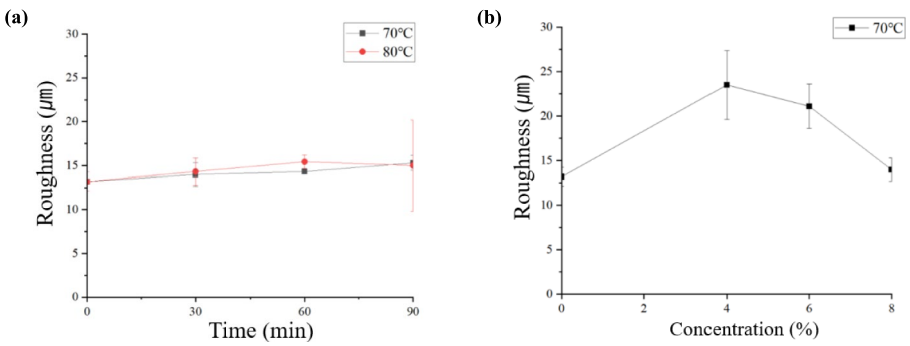


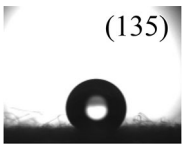
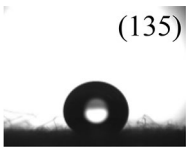
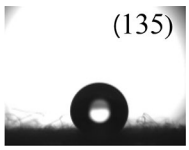
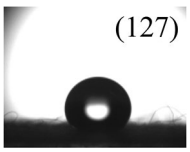
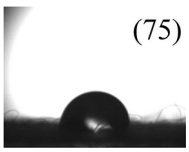
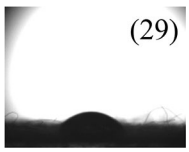
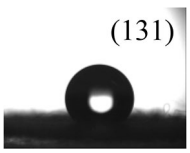
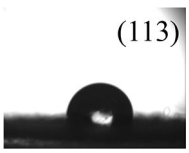
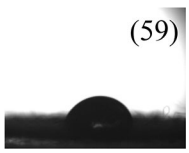
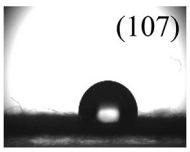
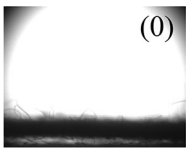
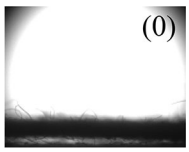
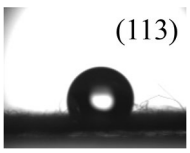
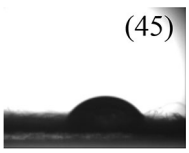
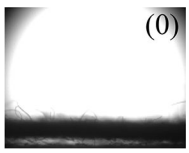
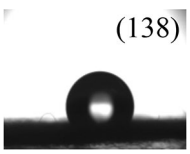
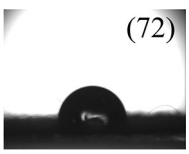
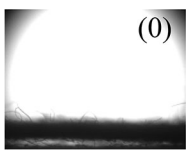
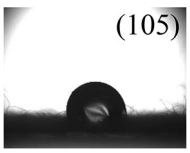
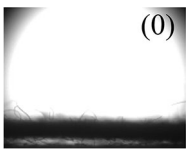
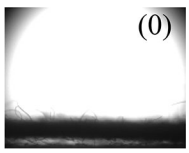
Fig. 5 Roughness of PET **a** at different temperatures and times under 8% NaOH concentration and **b** at different NaOH solution concentrations at 70℃ for 30 min

continuous etching to remove finer asperities, temporarily flattening the surface (Gupta et al., 2014).

Changes in the water contact angle by alkaline treatment

Table 8 shows the water contact angles of samples with surface roughness altered by etching under different alkaline treatment temperatures and durations. The untreated sample exhibited a water contact angle of 135°. For alkaline-treated samples, the water contact angle was still over 100° within one second, indicating hydrophobicity. This behavior is attributed to fine fibers on the fabric's surface, which temporarily

Table 8 Water contact angle of the PET fabric at different temperatures and times under 8% NaOH concentration

Conditions		Time			
		1 s	10 s	20 s	Lapsing time (s)
Untreated		 (135)	 (135)	 (135)	30 or more
70℃	30 min	 (127)	 (75)	 (29)	30 or more
	60 min	 (131)	 (113)	 (59)	30 or more
	90 min	 (107)	 (0)	 (0)	10
80℃	30 min	 (113)	 (45)	 (0)	20
	60 min	 (138)	 (72)	 (0)	20
	90 min	 (105)	 (0)	 (0)	5

The number in parentheses indicates the water contact angle (°)

formed air pockets between the surface and the water droplet. Over time, as the air pockets dissipated, the droplet was gradually absorbed into the fabric.

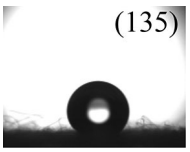
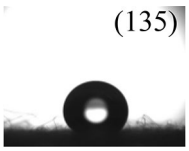
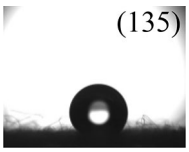
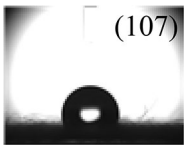
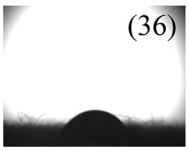
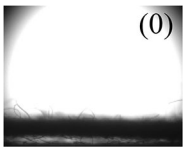
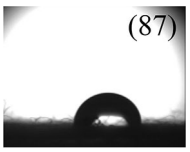
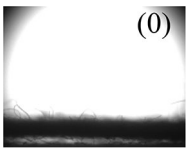
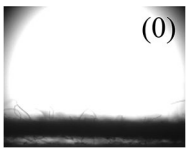
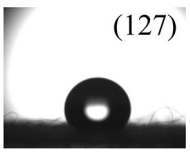
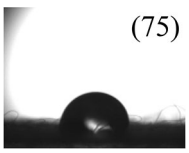
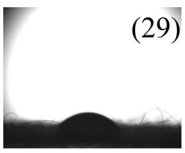
As the temperature and duration of alkaline treatment increased, the time required for the fabric surface to become completely wet decreased. The sample treated at 70 °C for 30 min took over 30 s to fully wet, while the sample treated at 70 °C for 90 min required less than 10 s. Similarly, the sample treated at 80 °C for 30 min took 20 s, whereas the sample treated at 80 °C for 90 min absorbed the droplet in under 5 s. This trend is linked to the increased hydrophilic groups and surface craters caused by alkaline hydrolysis (Han et al., 2016). The sample treated at 80 °C for 90 min exhibited the fastest wetting because of enhanced reactivity with water droplets. In contrast, at the 60-min treatment, the surface likely became temporarily flattened due to etching, delaying absorption. This suggests that wettability changes induced by alkaline hydrolysis are not linear (Čorak et al., 2022) but result from a complex interplay of physical and chemical modifications.

Additionally, surface change analysis indicated approximately a 14% reduction in fiber diameter from alkaline hydrolysis, which increased the spacing between fibers and likely influenced the water contact angle. Such rapid wetting behavior can be interpreted not only as a result of increased surface roughness, but also as an effect of chemical surface modification. Alkaline hydrolysis cleaves the ester bonds in PET, generating hydrophilic functional groups such as carboxyl (–COOH) and hydroxyl (–OH), which are well known to enhance surface energy and hydrophilicity (Başyiğit, 2018; Kodrić et al., 2025; Parvinzadeh, 2012). Although chemical analyses such as FTIR were not conducted in this study, previous literature has sufficiently demonstrated the introduction of these functional groups through alkaline treatment. This chemical modification is considered to have contributed to the reduction in contact angle observed in the present study. Therefore, it can be interpreted that the improvement in the wettability of PET fabrics resulted from a combined effect of both physical surface roughness and chemical surface modification.

Table 9 presents water contact angles of PET fabrics treated with sodium hydroxide (NaOH) solutions at 4%, 6%, and 8% concentrations. The sample treated with 6% NaOH had the smallest water contact angle and the fastest absorption time, followed by the samples treated with 4% and 8% NaOH. This trend appears to be connected to the surface roughness of the PET fabric (Fig. 5b), which initially increased with the NaOH concentration, peaking at 4%, but subsequently decreased due to surface etching at the 8% concentration. While the highest surface roughness was observed at 4%, the water contact angle was not solely dependent on roughness. Instead, it was influenced by a combination of the surface roughness and the amount and distribution of the hydrophilic functional groups. The sample treated with 6% concentration demonstrated minimized water contact angle, likely owing to the sufficient introduction of hydrophilic groups and relatively high roughness. Moreover, this phenomenon suggests that both the surface's physical structure and chemical properties have a combined effect on the water contact angle.

Consequently, the physical (e.g., increased roughness, reduced fiber diameter) and chemical (e.g., introduction of functional groups) changes induced by alkaline treatment acted synergistically to enhance the surface wettability of PET fabrics. This

Table 9 Water contact angle of the PET fabric depends on the NaOH solution concentration (at 70℃ for 30 min)

Conditions	Time			
	1 s	10 s	20 s	Lapsing time (s)
Untreated	 (135)	 (135)	 (135)	30 or more
4%	 (107)	 (36)	 (0)	10
6%	 (87)	 (0)	 (0)	5
8%	 (127)	 (75)	 (29)	30 or more

The number in parentheses indicates the water contact angle (°)

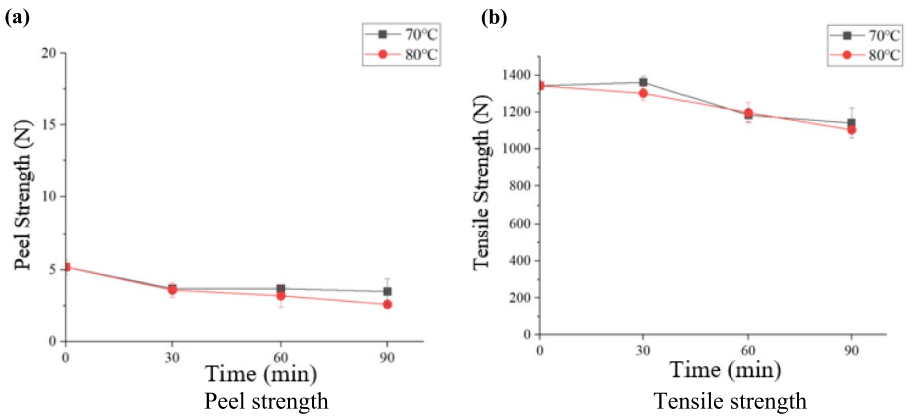


Fig. 6 Peel strength and tensile strength of 3D-PCF depending on the NaOH treatment time and temperature under 8% NaOH concentration

suggests that the improvement in wettability cannot be attributed solely to changes in surface roughness, but rather to a combined effect of complex surface modification.

Impact of surface changes from the alkaline treatment on peel strength

Figure 6a shows the results of the peel strength of the 3D-PCF under different alkaline treatment times and temperatures. The untreated sample had a peel strength of 5.2 N,

while the sample treated at 80 °C for 90 min showed a reduction to 2.6 N, representing a 50% decrease. Peel strength generally declined by 30% to 50% as treatment time and temperature increased. This reduction is likely because of the smaller adhesive area caused by a 14% decrease in fiber diameter following alkaline treatment. Additionally, excessive treatment may have weakened the substrate fabric, further reducing peel strength. To evaluate mechanical property changes caused by alkaline treatment, tensile strength was measured (Fig. 6b). Treated samples exhibited up to a 10% decrease in tensile strength compared to the untreated sample. Alkaline hydrolysis breaks ester bonds, reducing fiber strength and weight. This process thins the fibers, increasing their susceptibility to stress-related breakage. Correlation analysis indicated that surface roughness increases peel strength (Han & Yun, 2024). However, adhesion between the fabric and polymer filament depends on multiple factors. Among these, changes to bulk properties, such as tensile strength and the substrate's mechanical integrity, significantly impact peel strength in 3D-PCF.

Figure 7a shows the peel strength results of the 3D-PCF treated with varying NaOH solution concentrations. Samples treated with 4% and 6% NaOH solutions exhibited peel strengths of 15.6 N and 15.9 N, respectively—an increase of up to 206%. In contrast, the sample treated with 8% NaOH showed a peel strength of 3.7 N, representing a 29% reduction. As noted earlier, roughness increased for all alkaline-treated PET fabrics. The 4% NaOH-treated sample had a roughness (R_a) value of 23.51 μm, reflecting a 78% increase. This enhanced roughness likely expanded the contact area, contributing to the observed peel strength improvement. Excessive etching at 8% NaOH concentration, however, removed nanoasperities from the fiber surface, smoothing it and reducing the surface roughness. Consequently, the contact area diminished, leading to decreased the peel strength. Figure 7b shows the tensile strength results. The alkaline-treated samples exhibited an increase in tensile strength of 1% to 3% compared to untreated samples, suggesting minimal changes in the inherent mechanical properties of PET fabric.

The differences in peel strength observed in Figs. 6 and 7 can be interpreted as the result of varying bonding strength, surface roughness, and chemical composition caused by differences in the severity of the alkaline treatment. From the perspective of bonding strength, the high-temperature and long-duration conditions in Fig. 6 induced excessive

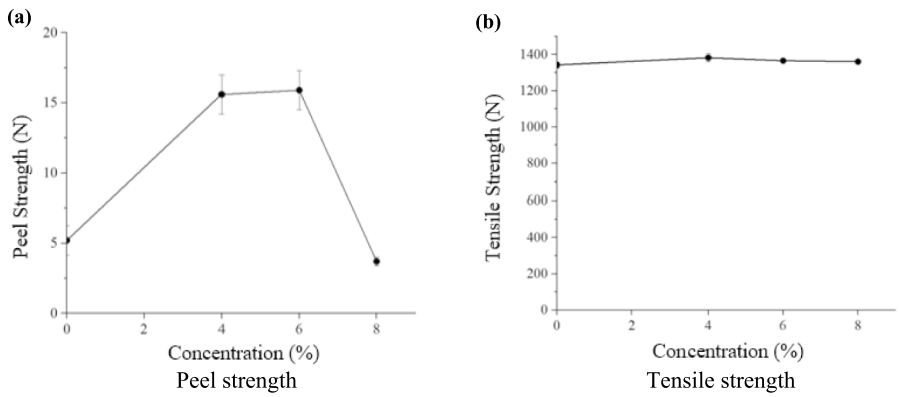


Fig. 7 Peel strength and tensile strength of 3D-PCF depending on the NaOH solution concentration (at 70℃ for 30 min)

hydrolysis within the fiber structure, leading to structural damage and a reduction in contact area, which in turn decreased peel strength. In contrast, the moderate concentration conditions (NaOH 4–6%) shown in Fig. 7 maintained the structural integrity of the fiber while increasing interfacial contact, thereby enhancing bonding strength. In terms of surface roughness, the moderate concentration condition preserved an appropriate level of nano-asperities, increasing surface roughness and improving interfacial bonding. However, under high-concentration conditions, excessive etching removed these nano-scale structures, resulting in a smoother surface and consequently a decrease in adhesive performance. From the viewpoint of chemical composition, the initial alkaline treatment introduced polar functional groups on the fiber surface, which contributed to adhesion by increasing interfacial energy. However, when the treatment was too aggressive, uneven decomposition and changes in surface composition occurred, compromising the uniformity of the bonding interface and negatively affecting adhesion. Taken together, these findings suggest that bonding strength, surface roughness, and chemical composition interact in complex ways depending on the alkaline treatment conditions, ultimately leading to variations in peel strength.

Furthermore, Through these two alkaline treatment experiments, it was confirmed that within a range where the bulk properties such as tensile strength do not significantly decrease, increasing the surface roughness through fiber surface modification enhances the peel strength of 3D printed composite fabrics.

Conclusions

This study aimed to investigate the effect of alkaline surface modification on the adhesion performance of 3D-PCF, with a particular focus on addressing the research gap concerning the influence of substrate fabric properties on adhesion strength. To this end, the concentration, treatment temperature, and duration of NaOH were systematically varied to analyze changes in fiber surface morphology and diameter, fabric weight and thickness, surface roughness, and wettability resulting from alkaline treatment. The impact of these physical property changes on the peel strength between the substrate fabric and the 3D printing filament was then evaluated. The key findings are as follows.

As temperature and treatment duration increased at an 8% NaOH concentration, PET fabric roughness increased, and fiber diameter decreased by approximately 14%. This effect was most pronounced in the sample treated at 80 °C for 90 min. Moreover, at an 8% NaOH concentration, weight and thickness reductions of approximately 13% and 15% were observed as temperature and duration increased. Weight and thickness changes were minor when NaOH concentrations of 4%, 6%, and 8% were applied at 70 °C for 30 min. Surface roughness measurements revealed slight increases in roughness with treatment time. At different NaOH concentrations, the R_a value increased by up to 78% at 4% and 6% concentrations but decreased at 8% because of surface etching. Lower concentrations produced significant micro-crater formation, increasing roughness, whereas higher concentrations smoothed the surface, reducing roughness.

In terms of the water contact angle changes after the alkaline treatment, time required for the fiber surface to fully absorb water decreased as treatment temperature and duration increased. The water contact angle, measured across different NaOH concentrations, showed that the sample treated with 6% NaOH had the

smallest contact angle and the fastest absorption time. In contrast, samples treated with 8% NaOH exhibited an increasing trend in water contact angle. This outcome is likely because of the combined effects of sufficient hydrophilic group introduction and increased surface roughness in the 6% NaOH-treated samples, which minimized the water contact angle. The interaction between the surface's physical structure and chemical properties significantly influenced these results. Notably, at 6% NaOH concentration, the presence of hydrophilic groups offset the effect of increased roughness, further enhancing hydrophilicity and reducing the water contact angle.

Peel strength measurements after alkaline treatment showed a decline of 30% to 50% as treatment duration and temperature increased. This reduction can be attributed to the decreased fiber diameter and reduced adhesion area caused by the treatment. However, peel strength improved significantly at NaOH concentrations of 4% and 6%, while it decreased at 8%. At lower concentrations, increased surface roughness enhanced the adhesion area, thereby improving peel strength. Conversely, at higher concentrations, excessive etching reduced surface roughness and adhesion area, leading to decreased peel strength. These findings confirm that appropriate alkaline treatment increases peel strength by enhancing surface roughness, while excessive treatment conditions reduce peel strength because of bulk strength degradation.

In conclusion, controlling the alkaline treatment concentration effectively enhances the peel strength of 3D-printed composite fabrics (3D-PCF) without compromising the adhesive surface area or inherent mechanical properties. Surface modifications that avoid bulk property degradation have proven effective in improving peel strength. When applied to high-performance textiles, such as protective gear or smart fabrics, these modifications are expected to extend functional lifespans and enhance overall product performance. This study focused on reproducibility and trend analysis of the experimental results through repeated measurements rather than relying on statistical significance testing. Further studies will employ statistical methodologies and mechanistic approaches to develop a more robust and systematic framework for the quantitative evaluation of the adhesion mechanisms of 3D-PCF. Furthermore, future research should explore a range of 3D printing process parameters to perform in-depth analyses—using SEM and optical microscopy—of how surface treatment affects print quality and layer morphology, and should supplement peel strength and tensile strength tests with bending, fatigue, and laundering durability assessments to comprehensively evaluate 3D-PCF durability under various mechanical and environmental loads.

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Not applicable. IRB permission is not applicable because there were no human or animal related experiments in this study.

Author contributions
YH conceived the ideas, designed the experiments, performed the experiments, collected the data, interpreted the results, and drafted the manuscript. CY supervised the experimental design, reviewed the experimental results, and contributed to manuscript preparation. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this article. Changsang Yun is an Executive Editor of ***Fashion and Textiles***. Executive Editor status has no bearing on editorial consideration.

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