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Effect of substrate fabric characteristics on the peel strength of 3D-printed composite fabrics

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Abstract

This study aimed to analyze those factors affecting the adhesion between substrate fabrics and 3D printing filaments by evaluating the influence of fabric surface characteristics, fiber composition, yarn type, and the fabric's structure. The results showed that among nylon, PET, and cotton, nylon demonstrated the highest peel strength; however, overall, surface characteristics had a more significant impact on adhesion than fiber composition, and in terms of yarn type, fabrics made from staple fibers had higher peel strength than those made from filament yarns, which is probably due to the rougher surface of staple yarns enhancing adhesion. Regarding fabric structure, among woven, knitted, and nonwoven fabrics, nonwoven fabrics demonstrated the highest peel strength, confirming that the structure and density of the fabric play a crucial role in adhesion. It was also found conclusively that fabric surface roughness and porosity affect peel strength significantly, with rougher surfaces and higher porosity leading to increased adhesion. This is because rougher surfaces provide more area for adhesion, and higher porosity allows the molten 3D filament to penetrate more easily between the fibers, thereby improving adhesion. This study provides practical guidelines for improving the adhesion characteristics of 3D-printed composite fabrics.

Keywords: 3D printing, 3D-printed composite fabric, Peel strength, Surface roughness, Porosity

Introduction

3D printing, as a form of additive manufacturing technology, has made significant advances over recent years (Chakraborty & Chandra Biswas, 2020; Jiang et al., 2017; Pei et al., 2015; Spahiu et al., 2020; Xiao & Kan, 2022). This technology is gaining widespread interest across various industries, with continued growth expected, particularly in the textile and fashion sectors (Chakraborty & Chandra Biswas, 2020; Li et al., 2024; Sanchez et al., 2020; Xiao & Kan, 2022). One of the widely used 3D printing methods, fused deposition modeling (FDM), is an additive manufacturing technique by which thermoplastic filaments are melted and extruded through a nozzle. In this process, layers of thermoplastic filament are deposited successively to create a three-dimensional object (Jung & Lee, 2023; Manaia et al., 2023). By printing thermoplastic filaments onto

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fabric using the FDM method, the resulting 3D-printed composite fabric (3D-PCF) can maintain the tensile strength and flexibility typical of conventional clothing materials while also enabling the creation of various three-dimensional designs. Additionally, it can contribute to the development of new applications and functional products, such as smart textiles for wearable devices that integrate IT with textile products (Lee & Lee, 2024; Xiao & Kan, 2022).

Previous studies on the mechanical properties of 3D-PCF, especially adhesion, have mainly focused on analyzing the factors that affect adhesion in the two categories of substrate fabrics and the 3D printing process. One of the critical printing parameters influencing the adhesion of 3D-PCF is the distance between the nozzle and the print bed (the Z-distance). Reducing this distance increases adhesion, as the pressure from the nozzle at a shorter distance forces the polymer into the fabric's pores with greater force (Spahiu et al., 2018). Additionally, the temperature of the print bed and the extruder is a crucial factor. Increasing the temperature of both reduces the viscosity of the melted 3D filament during printing, thereby allowing the polymer to penetrate deeper into the fabric (Cheung & Choi, 2023; Spahiu et al., 2018).

Previous studies have reported that the adhesive strength of 3D-PCF depends on the substrate fabric, with key parameters including fiber composition (Demir & Seki, 2023; Korger et al., 2020; Mpofu et al., 2019; Sanatgar et al., 2017), yarn type (Meyer et al., 2019), yarn thickness (Silvestre et al., 2023), warp and weft density (Mpofu et al., 2019; Eutionnat-Diffo, 2020), fabric thickness (Korger et al., 2016; Mpofu et al., 2019; Störmer et al., 2021), and fabric structure (Eutionnat-Diffo, 2019; Eutionnat-Diffo, 2020; Sanatgar et al., 2017). Korger et al. (2020) also noted that the polarity interaction between the 3D printing filament and the fabric printed on it, rather than the chemical composition of the substrate fabric, affects adhesion. Studies on adhesion based on yarn type have indicated that staple yarn fabrics demonstrate higher adhesion than filament yarn fabrics (Meyer et al., 2019), which is due to the partially embedded fibers protruding from the fabric into the 3D-printed polymer. Silvestre et al. (2023) reported that as yarn thickness increases, the gaps between the yarns widen, increasing the penetration of the 3D printing filament, which extends the available adhesive surface area between the substrate and the 3D printing filament, thereby improving adhesion. In contrast, higher warp and weft density have been found to decrease adhesion (Mpofu et al., 2019; Sanatgar et al., 2017), which is attributed to the relationship between the warp and weft density and the fabric cover factor. The cover factor refers to the proportion of the fabric area covered by the warp and weft yarns; as the warp and weft density increases, the fabric cover factor also increases, leading to a reduction in fabric porosity. This reduction in porosity limits the diffusion of the 3D printing filament into the fabric, reducing the surface area that is available for adhesion, and thereby decreasing adhesive strength (Eutionnat-Diffo et al., 2019). The average pore size of the fabric also affects adhesion (Eutionnat-Diffo et al., 2019). Thicker fabrics demonstrate higher adhesion (Lekeckas et al., 2023; Meyer et al., 2019; Mpofu et al., 2019), and Korger et al. (2016) found using a visual assessment that rough and thick fabrics have better adhesion. Studies on the structure of substrate fabrics have mainly focused on woven and knitted fabrics, with reports indicating that knitted fabrics demonstrate relatively high peel strength when a 3D printing filament is applied, due to the porous fiber surface of the fabric (Narula et al., 2018). In addition,

Malengier et al. (2017) proposed a standardization of adhesion tests to ensure consistency in the research results related to polymers printed onto substrate fabrics. Since standards for the evaluation of 3D-PCF have not yet been established, studies proposing methods for adhesion evaluation to achieve consistent research results are still ongoing. This study aims to investigate the impact of substrate fabric characteristics on the strength of adhesion between the substrate fabric and the 3D printing filaments. To achieve this, the study assessed the surface properties of the substrate fabric and the types of fabrics (including fiber composition, yarn type, and fabric structure), and evaluated the adhesion strength of the 3D printing filaments using peel tests. This is expected to provide a clearer understanding of the adhesion mechanisms of 3D-PCF and offer essential foundational data for the development of smart textiles and functional products in the future.

Methods

Materials

Filament for 3D printing

The characteristics of the filaments for 3D printing are listed in Table 1. The thermoplastic polyurethane (TPU) filament used in this study was supplied by eLastic 3D filament (ESUN). Thermoplastic polyurethane is a material known for its flexibility, durability, and ease of deformation and recovery. It is mainly used in the field of textiles and apparel for 3D printing applications.

Substrate fabrics

The characteristics of the substrate fabrics used in the study are shown in Table 2. Six fabrics with varying fiber compositions, fabric structures, and yarn types were used.

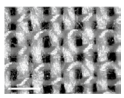
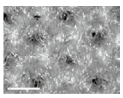
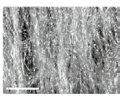
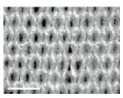
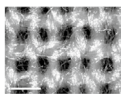
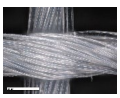
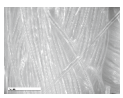
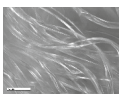
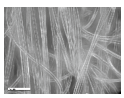
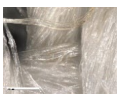
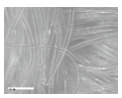
3D printing process

The 3D printer used was the STYLE NEO-A31C (Cubicon, Korea). Fabric of 300 mm × 300 mm was placed on the heating bed, and a 3D model of 200 mm × 25 mm × 1 mm, designed using Rhinoceros CAD software, was then printed onto the fabric (Fig. 1). The fill density of the tracks was set to 20%, the printing speed was 30 mm/s, the nozzle diameter was 0.4 mm, and the nozzle temperature was set to 240 °C. The Z-distance was set according to the thickness of each fabric sample. The Z-offset (the distance between the nozzle and the fabric) was set to 10 (minimum unit)

Table 1 Properties of thermoplastic polyurethane filaments

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 Properties of the substrate fabric

Sample code	PWF	PWS	PKT	PNW	CWS	NWS
Fiber composition	PET	PET	PET	PET	cotton	nylon
Yarn type	filament yarn	spun yarn	drawn textured yarn	–	spun yarn	spun yarn
Fabric Structure	woven	woven	knitted	nonwoven	woven	woven
Weight (g/m^2)	61.4	141.1	206.7	68.1	119.5	142.6
Thickness (mm)	0.13	0.31	0.89	0.30	0.23	0.39
Fabric density (counts/5 cm)	79×68	53×51	20×27	–	116×60	39×29
Yarn Thickness (μm)	140.8	296	276.1	–	203.6	482.0
×100 (Scale bar: 1 mm)						
×1000 (Scale bar: 100 μm)						

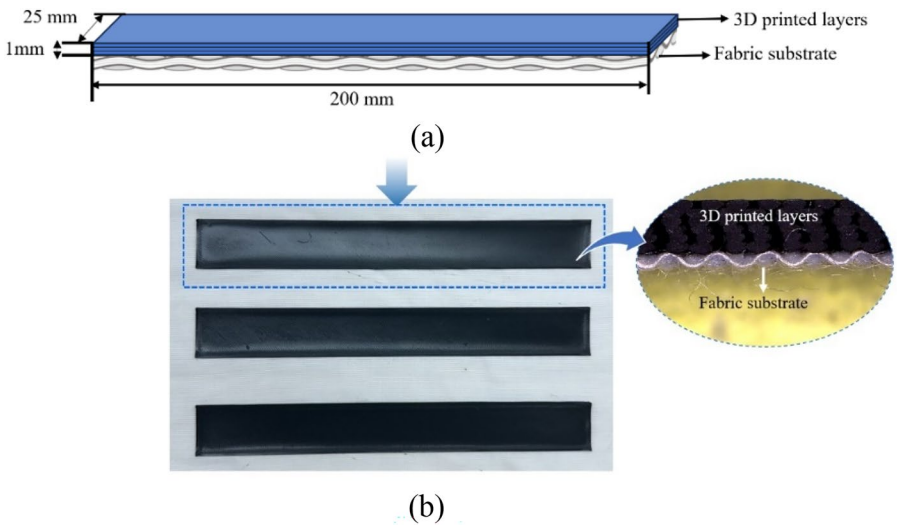


Fig. 1 3D-PCF of a model size (200 mm×25 mm×1 mm), and b actual output

per 0.01 mm, and this value was adjusted in 10-unit increments according to the thickness of the fabric. For example, for a fabric thickness of 0.31 mm, the initial Z-offset was set to 310. The Z-offset was then reduced gradually in 10-unit increments to determine the minimum distance at which the 3D filament could be extruded from the nozzle onto the substrate fabric. Using this method, the Z-distance for each fabric was set, and 3D-PCFs were produced. The 3D printing parameters and Z-distances according to fabric thickness are shown in Tables 3 and 4.

Table 3 3D printing conditions

Condition	Value
Temperature of nozzle (℃)	240
Temperature of heating bed (℃)	60
Printing speed (mm/s)	30
Infill (%)	20

Table 4 Z-distance depending on fabric thickness

Sample code	Thickness (mm)	Z-distance (Z-offset)
PWF	0.13	100
PWS	0.31	300
PKT	0.89	850
PNW	0.30	300
CWS	0.23	200
NWS	0.39	350

Physical properties

Weight and thickness

The mass per unit area was measured according to ISO 3801:1977. A fabric of 100 mm × 100 mm was weighed five times using an electronic balance (WBA-320, Daihan Scientific Group, Korea), and the average value was then converted to g/m^2. The thickness was measured according to ISO 5084:2011 using a thickness gauge (Hanwon Testing Co., Korea). The average thickness was calculated from measurements made at five different locations on each sample.

Density

The density of the samples (counts/5 cm) was measured using the ISO 7211-2:2024B method (the thread count method). The number of threads visible within a unit area of the thread count gauge was counted. Measurements were taken from at least five places on each sample.

Porosity of the fabric

The porosity of each fabric sample was measured using a 3D X-ray microscope (XRM; X-radia 510 Versa, Carl Zeiss, Germany). The XRM provides non-destructive 3D imaging, which facilitates the analysis of the composite material distribution, orientation, pore distribution, and internal structure. To acquire a 3D image, a 7.0 W power source, 80 kV voltage, and 5 μm resolution were used. The 2D images obtained were stacked to create a 3D image, using Dragonfly Pro software (Object Research Systems, Canada).

Surface characteristics

Morphology

The surface morphology was observed using a digital microscope (Smart Zoom, Carl Zeiss, Germany).

Surface roughness

The measurement of surface roughness was carried out using a confocal laser scanning microscope (CLSM, LMS 900, Carl Zeiss, Germany) following ISO 4287. The measurements were conducted at both micro scale (600 μm × 600 μm) and macro scale (5 mm × 5 mm). The centerline average roughness (R_a) and the arithmetic mean of the waviness profile (W_a) were measured (Fig. 2). The cutoff value refers to the threshold used to filter specific frequency components, which assists with noise removal and signal separation. The waviness profile (W_a) was obtained by filtering out long and short wavelengths using λ_f and λ_c filters, respectively. The roughness profile (R_a) was derived using a high-pass filter with the cutoff value λ_c, which suppresses long wavelengths. The cutoff value λ_c served as the boundary for distinguishing between roughness and waviness, with λ_c set to 0.12 mm and 0.80 mm to include both the roughness and waviness elements. For all fabrics, measurements were taken in both the warp and weft directions at each scale (micro and macro) with five measurements taken per direction. The measurements were repeated at five different locations on each fabric sample to obtain the mean value. During micro-scale (R_a) measurements, only the fabric areas were considered, avoiding the pore regions.

Adhesion properties

Since there is no standard for measuring the strength of adhesion between substrate fabrics and 3D printing filaments, the adhesion strength of the 3D printed composites was measured according to the ISO 11339 standard using a Universal Testing Machine (5982 Series, Instron, USA) (Fig. 3-a). As shown in Fig. 3-b, a 3D-PCF was placed between the upper and lower clamps. The lower clamp fixed the substrate fabric, while the upper clamp did the TPU printed on the substrate fabric. The upper

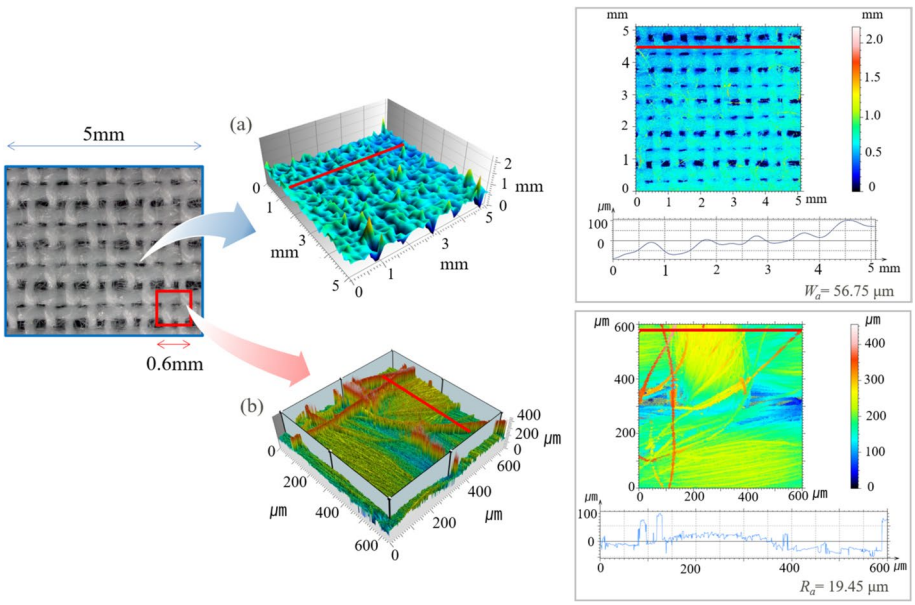
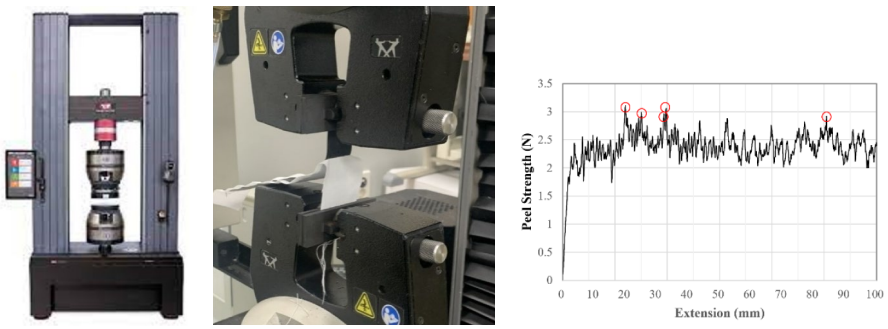


Fig. 2 Roughness of a macro scale (W_a) and b micro scale (R_a)



(a) Universal testing machine (b) Peel strength test (c) Highest peak

Fig. 3 Peel strength measurement

clamp was then moved at a tensile speed of 100 mm/min. The test was repeated five times, and the average of the five highest peak values was used (Fig. 3-c).

Statistical analysis

To identify those factors affecting adhesion strength among the physical properties of the fabrics, Pearson correlation analysis was performed using SPSS ver. 25 (IL, USA).

Results and Discussion

Effect of fabric surface and pore characteristics on peel strength

The surface and pore characteristics of the substrate fabric have a significant impact on the strength of adhesion, making it crucial to examine the surface of the substrate fabric before 3D printing. The pores in the fabric are directly related to the adhesion of the 3D printing polymer, as they allow the molten polymer to penetrate. As shown in Table 2, substrate fabrics made from filament yarn (PWF) have a smooth surface, whereas nonwoven fabrics (PNW) and fabrics made from textured yarns and spun yarns (PKT, PWS, CWS, and NWS) have a rough surface due to the presence of fiber protrusions and roughness from the yarn twists.

Figure 4 and Table 5 show the results of surface roughness by using a non-contact confocal microscope. As observed in Fig. 4, R_a and W_a showed similar trends, but the W_a values were higher than the R_a values. This indicates that the amplitude of the waviness profile is greater than that of the R_a profile due to the surface topography created by the warp and weft directions. The highest R_a value was found in PNW, followed by NWS and PKT. In contrast, W_a values were highest for PKT, after PNW. This difference can be attributed to the fact that PKT has fewer red areas (indicating a rough surface) than NWS in R_a measurements, as shown in Table 5. The surface porosity and irregular yarns of PKT affect the waviness significantly, resulting in higher W_a values, while the surface fuzz and staple fibers in NWS contribute to higher R_a values. The color gradient in the surface topography moving from blue to red indicates increasing waviness and roughness, indicating that a redder surface is rougher.

Pearson correlation analysis was performed to determine which measurement scale has a higher correlation with peel strength. The correlation coefficient for R_a was 0.920 ($p < 0.001$), while that for W_a (waviness) was 0.654 ($p < 0.01$). This indicates that R_a has

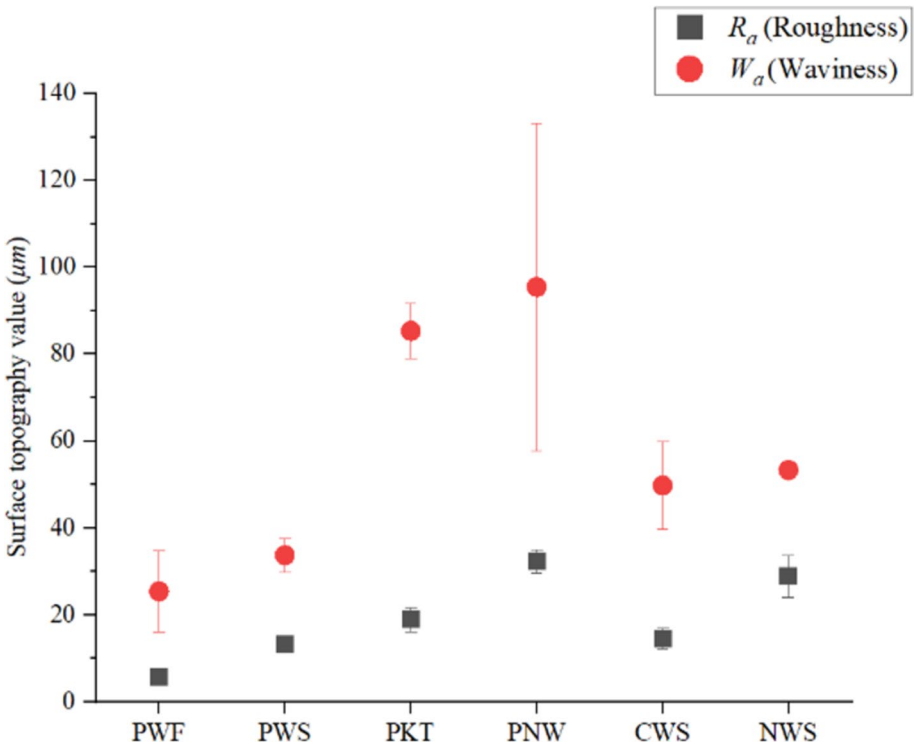
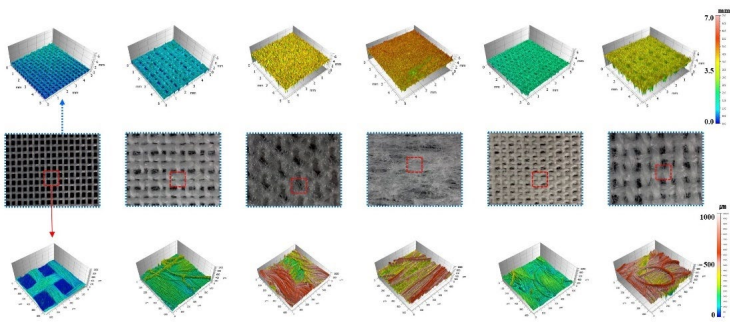


Fig. 4 Surface roughness and waviness

Table 5 Topographic map of the fabric surface (W_a and R_a)

Roughness profile	PWF	PWS	PKT	PNW	CWS	NWS
Macro Scale **(5.0 mm × 5.0 mm)** Waviness (W_a) Image						
Micro Scale **(0.6 mm × 0.6 mm)** Roughness (R_a) Image						

stronger explanatory power for peel strength than W_a. Therefore, R_a would be the primary focus for analyzing surface roughness data going forward.

The high R_a values for PNW and NWS indicate rough surfaces. Surface roughness is associated with fabric density and porosity; lower fabric density and higher porosity typically result in increased roughness (Akgun, 2015), and an increase in porosity means a higher frequency of pores, which ultimately leads to increased surface roughness. With their relatively high surface fuzz and low density, PNW and NWS,

are likely to have more spaces between fibers, which contributes to greater surface roughness. Conversely, PWF, woven from filament yarns with minimal fuzz, has the lowest R_a value. Despite the expectation that PKT, with its lower density than NWS, would have higher roughness, NWS shows higher roughness than PKT. This is probably due to the impact of the yarn fuzz and thickness on surface roughness, which outweighs the effect of density.

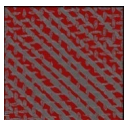
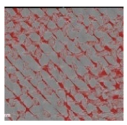
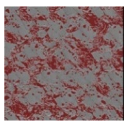
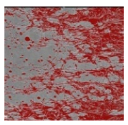
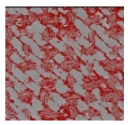
The results of measuring the porosity per unit area using a 3D X-ray microscope are displayed in Table 6. These results were obtained through 3D tomography, indicating the size of the spaces within the fabric that allow air or liquid to pass through. Porosity is influenced by factors such as yarn diameter, fabric density, and fabric thickness (Xie, 2002). In each image of the porosity area in Table 6, the red sections represent the porosity at the topmost layer only. The porosity of PNW was the highest at 39.6%. This is likely due to the wide surface area where pores can occur between fibers, followed by a decrease in porosity in the order of PKT > PWF > NWS > PWS > CWS. Due to its bulky structure compared to filament or staple samples, PKT has a low yarn ratio within a unit area and appears to have more spaces containing air. Therefore, it can be confirmed that knitted or non-woven fabrics, rather than woven fabrics, have greater porosity and that porosity increases with an increase in fabric thickness and a decrease in the yarn density (Mpofu et al., 2019; Narula et al., 2018; Sanatgar et al., 2017).

The results of measuring peel strength with reference to porosity and roughness (R_a) are shown in Fig. 5. It was confirmed that the values of roughness and porosity increased with the increase in peel strength. The fabrics PNW and NWS exhibited high porosity values of 39.6% and 33.5%, respectively, along with high roughness values. Consequently, they also showed high peel strength. This is because higher porosity allows the molten 3D filament to penetrate more easily between the fibers, and a rougher surface increases the adhesive surface area, thereby enhancing peel strength. These results are consistent with the findings of Korger et al. (2020), Silvestre et al. (2023), and Eutionnat-Diffo et al. (2019), who reported that surface roughness, irregularities, and high porosity of fibers significantly influence adhesion strength.

Effect of *fiber* composition on peel strength

The substrate fabrics can be categorized based on fiber composition into polyethylene terephthalate (PET), cotton, and nylon, with a focus on plain woven fabrics made from spun yarns. The peel strength was examined based on these fiber compositions. In this study, nylon showed the highest peel strength, followed by PET and cotton (Fig. 6). Compared to PET fibers, nylon fibers have carboxyl (-COOH) and amino ($-NH_2$) groups at

Table 6 Pore area and porosity (%)

	PWF	PWS	PKT	PNW	CWS	NWS
Pore area						
Porosity (%)	33.7	19.9	36.7	39.6	19.0	33.5

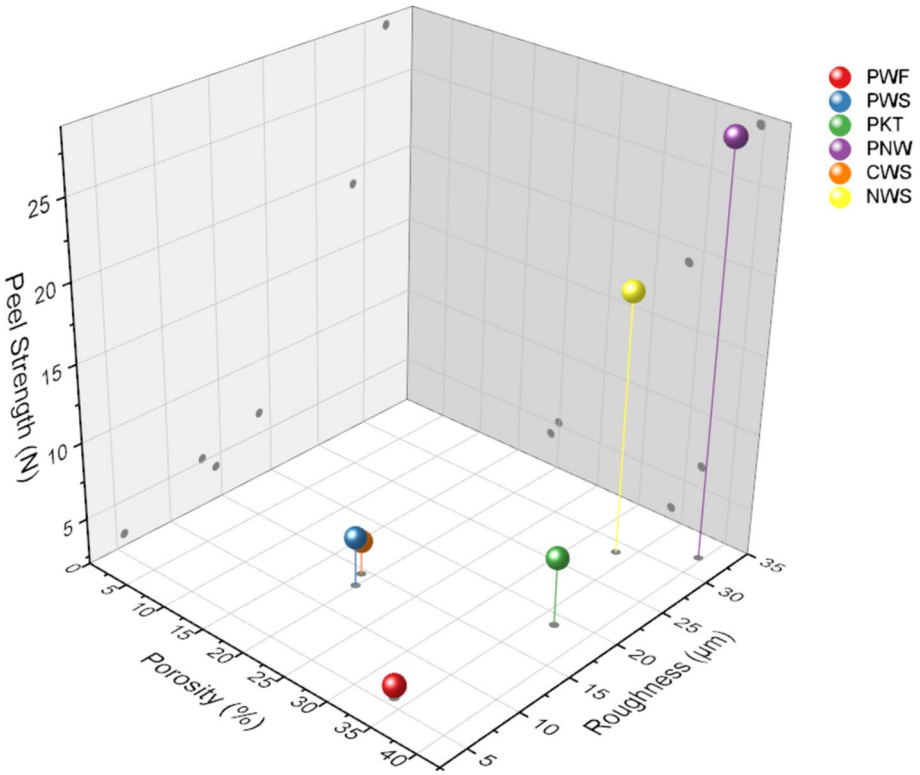


Fig. 5 Peel strength according to roughness (R_a) and porosity

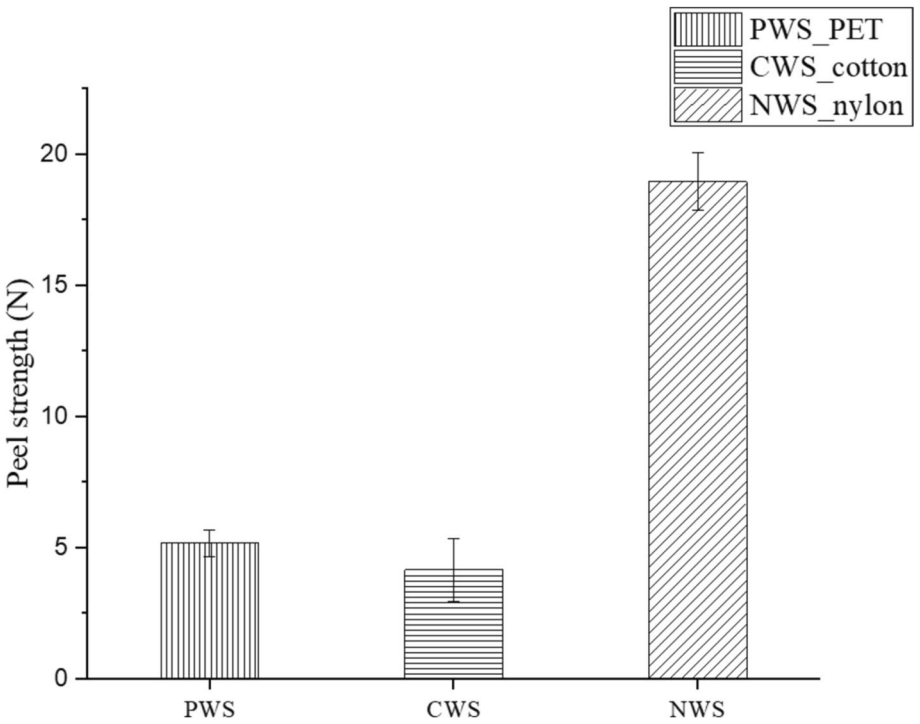


Fig. 6 Peel strength according to fiber composition

the end of polymer chains, making them relatively less hydrophobic, although both fibers exhibit hydrophobic characteristics. Korger et al. (2020) noted that to enhance adhesive effects, the substrate fabric should have functional groups that can interact with a 3D printing filament. In the study by Mpofu et al. (2019), it was also found that cotton fabrics exhibited higher adhesion compared to PET fabrics. However, Against expectations, cotton demonstrated the lowest peel strength, suggesting that factors other than fiber composition had a greater impact on peel strength. As shown in Fig. 5, peel strength showed a strong correlation with roughness (R_a), indicating that surface characteristics such as fuzziness or pores had a more significant impact on peel strength than the chemical bond between the fabric and polymer. Additionally, in the case of unscoured cotton, various pastes or oils (such as spinning oils, knitting oils, weaving oils, and sizing agents) used during fiber processing, which coat the surface and impart hydrophobicity, likely also influenced the resultant poor adhesion strength. Typically, the assessment of cotton fabric characteristics necessitates examination of both pre- and post-scouring states. However, this study is limited to the analysis of cotton fabrics prior to scouring, indicating a need for further examination.

Effect of yarn type on peel strength

The results of peel strength, categorized by filament yarn and spun yarn, are shown in Fig. 7. Among these, PNW, made of staple fibers arranged in a web-like structure with an irregular orientation, showed the highest peel strength, followed by the spun yarn NWS. There is little variation in peel strength among the other fabrics. For PNW and NWS, the roughness of the fabric surface, caused by the twist, fuzz, and unevenness from the spun yarn, appears to have affected the peel strength. Fibers protruding from the

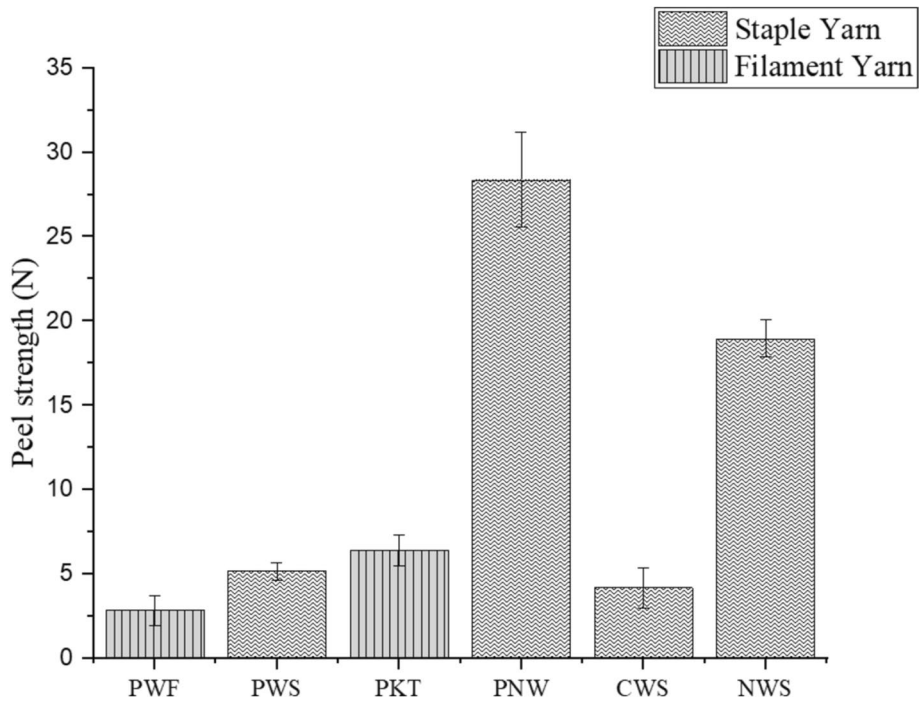


Fig. 7 Peel strength according to yarn type

fabric are partially embedded in the 3D-printed polymer, increasing the adhesive surface area and consequently enhancing the peel strength (Malengier et al., 2017). Additionally, the roughness of PNW and NWS, which are 32.3 and 28.8, respectively, are significantly higher than the other fabrics (Fig. 4). Therefore, it is thought that PNW and NWS showed significantly higher peel strength. Conversely, PWS and CWS samples, despite being spun yarns, demonstrated lower peel strengths. This can be attributed to their lower roughness values, and other factors such as fabric density or porosity may have also influenced the results. The lower peel strength of PWF and PKT, both woven with filament yarns, is probably due to the relative lack of fuzz, resulting in insufficient adhesive surface area. Meyer et al. (2019) reported that spun yarns, being firmly fixed within the fabric and partially embedded in the 3D filament, can enhance peel strength more effectively than filament yarns.

Effect of fabric density and structure on peel strength

Fabric density influences surface roughness and porosity, and a higher fabric density generally leads to decreased porosity and surface roughness (Akgun, 2015). Analysis of the warp and weft densities of the fabrics revealed that CWS had the highest warp density, followed by PWF, PWS, NWS, and PKT (Table 2). For weft density, PWF and CWS showed the highest values, followed by PWS, NWS, and PKT (Table 2). The peel strength as a function of fabric density is shown in Fig. 8. Higher warp and weft densities correspond to lower peel strength. This trend is seen in CWS and PWF, which have high

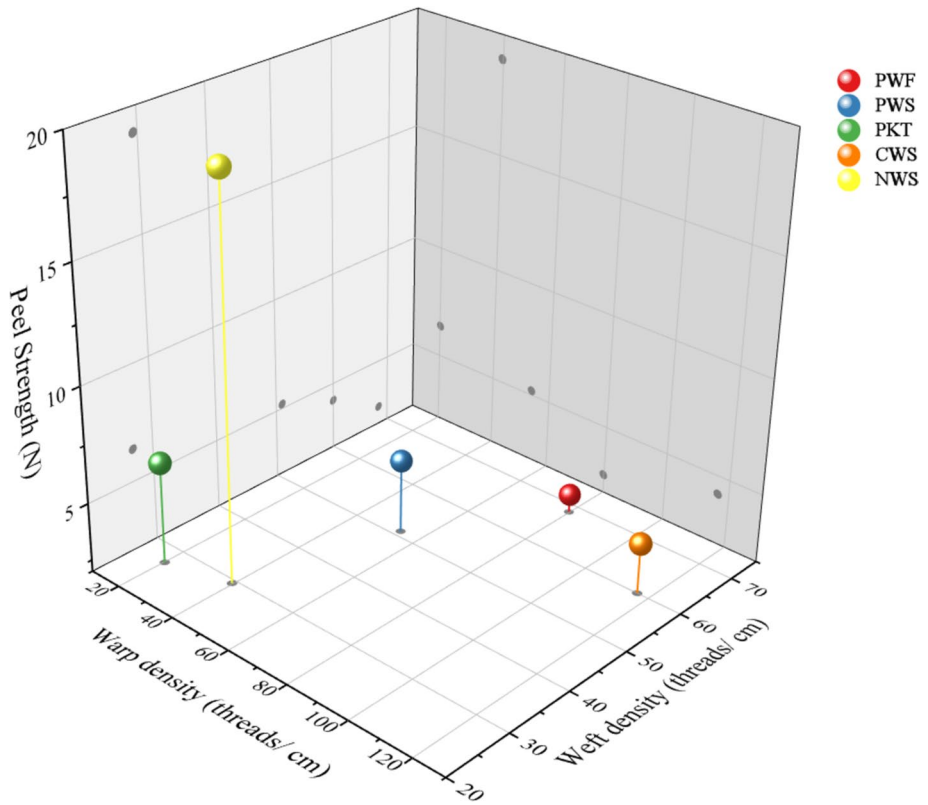


Fig. 8 Peel strength according to warp density and weft density

warp and weft densities but lower peel strengths. This finding aligns with the studies by Mpofu et al. (2019) and Sanatgar et al. (2017), who reported that higher fabric densities reduce porosity, thereby decreasing adhesion strength. Higher density results in lower fabric porosity, which restricts the diffusion of the 3D polymer into the fabric. Consequently, the adhesive surface area on the fabric decreases, leading to reduced strength of adhesion.

The peel strength based on fabric structure, categorized into woven, knitted, and nonwoven fabrics, is shown in Fig. 9. The nonwoven fabric PNW showed the highest peel strength, followed by the woven fabric NWS. From a structural perspective, nonwoven fabrics show more than four times higher peel strength than woven and knitted fabrics. This is attributed to the nonwoven fabric's structure, which has a higher porosity and a cross-lay arrangement than woven and knitted fabrics. This structure provides a greater open area, allowing polymers to penetrate easily through the fabric's pore structure and entangle, thereby enhancing adhesive strength. In contrast, the knitted fabric PKT, despite having a higher porosity than the woven fabric NWS, as shown in Fig. 5, showed lower peel strength. This suggests that even with a higher porosity, a lesser roughness can result in reduced peel strength. Therefore, the relatively low peel strength of PKT is likely due to its lesser roughness.

Physical properties affecting peel strength in 3D-PCF

To examine the correlation between peel strength and key variables such as weft density, warp density, roughness (R_a), waviness (W_a), porosity, weight, and thickness, Pearson's correlation analysis was conducted. The results indicate that peel strength is correlated

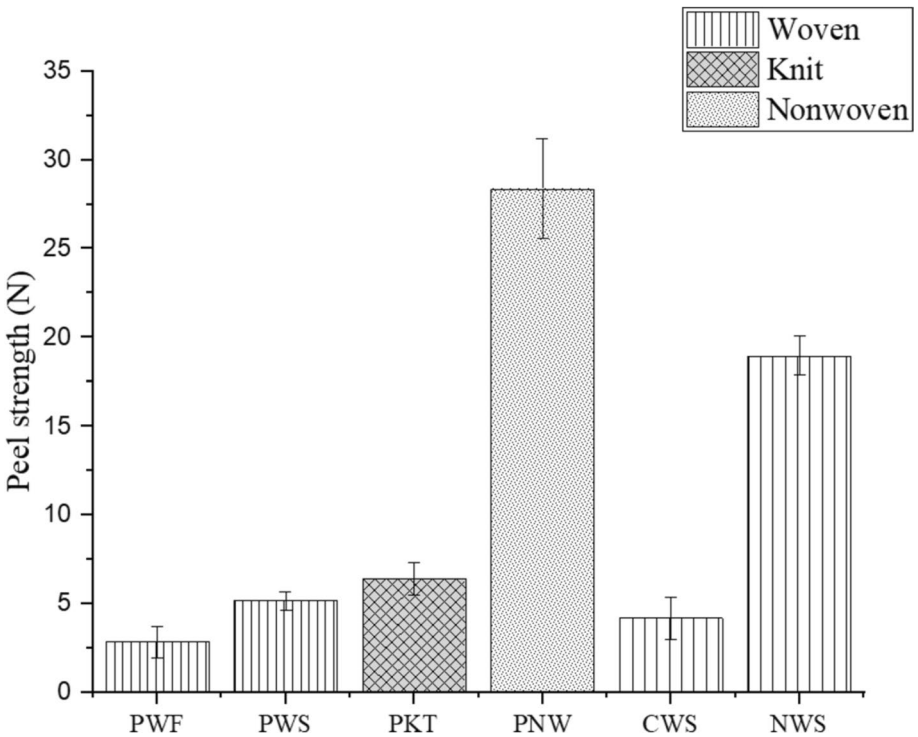


Fig. 9 Peel strength according to the structure of the fabric

Table 7 Correlation analysis between key variables and peel strength

Variable	Peel Strength	Weft Density	Warp Density	Roughness (R_a)	Waviness (W_a)	Porosity	Weight	Thickness
Peel Strength	1							
Weft Density	0.682**	1						
Warp Density	− 0.460	0.830***	1					
Roughness (R_a)	0.920***	− 0.856***	− 0.511	1				
Waviness (W_a)	0.654**	− 0.801***	− 0.540*	0.758***	1			
Porosity	0.584*	− 0.482	− 0.642**	0.501*	0.607**	1		
Weight	− 0.270	− 0.865***	− 0.687**	0.068	0.230	− 0.114	1	
Thickness	− 0.016	− 0.831***	− 0.759***	0.253	0.584*	0.348	0.865***	1

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

significantly with roughness, waviness, weft density, and porosity (Table 7). Notably, roughness shows a stronger correlation with peel strength ($r = 0.920$, $p < 0.001$) than waviness ($r = 0.654$, $p < 0.01$). This suggests that the micro-texture of the fiber surface has a more significant effect on peel strength than the overall surface topography, including pores. In conclusion, while variables related to pores, such as waviness, porosity, and weft density, also influence peel strength to some extent, roughness remains the most significant factor. This indicates that the fine texture of the fabric surface, which affects the contact area, plays a more important role in determining peel strength than the proportion of pores.

Conclusions

This study aimed to analyze the effect of substrate fabric characteristics on the adhesion between the fabric and 3D printing filaments, evaluating such factors as surface properties, fiber composition, yarn type, and fabric structure. The surface and porosity characteristics of the fabric have a significant impact on the peel strength of 3D printing. Fabrics with greater surface roughness demonstrate greater peel strength, with a strong correlation between the mean roughness (R_a) and peel strength. Higher porosity facilitates better penetration by 3D printing filaments, further increasing the peel strength. Therefore, surface roughness and porosity are crucial variables in improving adhesion. Against expectations, the fiber composition had a different impact on peel strength. Nylon showed the highest peel strength, followed by PET and cotton. Although cotton has relatively more functional groups than nylon and PET, it showed lower peel strength, possibly due to the hydrophobic coating from pastes and oils used during manufacturing processes. This suggests that physical factors such as surface roughness and porosity have a more consequential effect on peel strength than fiber composition. Regarding yarn types, fabrics made from spun yarns showed higher peel strength due to increased surface roughness caused by yarn twist, fuzz, and irregularities. In contrast, PWS and CWS, despite being spun yarns, showed lower peel strength due to factors such as lower roughness, density, and porosity. Fabrics woven with filament yarns showed lower peel

strength than spun yarns, probably due to the relatively smaller adhesive surface area available for bonding. These results suggest that spun yarn fabrics have higher adhesion than filament yarn fabrics, indicating that spun yarn fibers are more effectively embedded in 3D filaments, thereby enhancing adhesive strength. Fabric density also affect peel strength. A higher fabric density generally leads to a reduced peel strength due to decreased porosity and restricted penetration by 3D printing filaments. Analysis of peel strength based on fabric structure revealed that nonwoven fabrics showed the highest peel strength. Nonwoven fabrics have larger voids between the fibers and a cross-lay structure, allowing 3D printing polymers to penetrate more effectively and enhance adhesion. Analysis of the correlation between peel strength and key variables revealed that peel strength had the strongest correlation with the fiber surface roughness (R_a), along with porosity and waviness (W_a). This indicates that the micro-texture of the fiber surface has a greater impact on peel strength than the overall surface topography, including the pores. Therefore, even if the porosity is high, a lesser roughness can result in reduced peel strength, suggesting that the fine texture of the fiber surface plays a more important role in determining peel strength than the proportion of pores. To enhance the adhesive properties of 3D-PFC, understanding the substrate fabric's characteristics is essential. Optimizing surface roughness and porosity can improve adhesion significantly. This study employed a singular type of 3D printing filament; however, it is imperativez to investigate the peel strength across a diverse range of filament types. Furthermore, considering the significant impact of substrate fabric surface characteristics on peel strength, there is a pressing need for in-depth research focused on exploring strategies for enhancing peel strength through surface modification.

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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

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Not applicable.

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