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Large-scale production of CNT reinforced PVC-based artificial leather

Abdulcabbar Yavuz [a,*], Musa Yilmaz [b], Necip Fazil Yilmaz [c,d]

[a] Gaziantep University, Department of Metallurgical and Materials Engineering, Sehitkamil 27310, Gaziantep, Türkiye
[b] Naci Topcuoglu Vocational School, Gaziantep University, Sehitkamil 27600, Gaziantep, Türkiye
[c] Gaziantep University, Department of Mechanical Engineering, Sehitkamil 27310, Gaziantep, Türkiye
[d] Hasan Kalyoncu University, Board of Trustees, 27010, Gaziantep, Türkiye

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ABSTRACT

Nanoparticle-reinforced polymers have been extensively studied at the laboratory scale for decades; however, their large-scale implementation in everyday applications remains limited. In this study, carbon nanotube (CNT)-enhanced PVC-based artificial leather was successfully fabricated and systematically characterized. The structural, optical, and mechanical properties of both neat and CNT-reinforced artificial leather were investigated through FTIR, UV–Vis spectroscopy, SEM, XRD, tensile, flexibility, abrasion, wear, and water contact angle measurements. Accelerated aging tests under UV and thermal exposure were also conducted. Although the addition of 0.5 wt% CNTs did not alter the surface structure—likely due to nanoparticle encapsulation within the polymer matrix—it significantly influenced other properties. The CNTs were generally well-dispersed with minimal agglomeration. Notably, the inclusion of CNTs enhanced tensile strength, reduced abrasion loss, and enabled control over the flexibility of the artificial leather. These findings demonstrate that even a small addition of CNTs can substantially improve the mechanical performance and durability of PVC-based artificial leather, highlighting its potential for broader practical applications.

1. Introduction

Composite materials are designed to integrate multiple functionalities into a single structure, offering enhanced performance compared to traditional materials [1]. A key strategy in achieving this is the incorporation of two-dimensional (2D) nanomaterials, which have shown great potential in significantly altering the bulk properties of the host matrix [2]. Nanomaterials such as MXenes, carbon nanotubes (CNTs), and graphene are particularly effective in improving magnetic, electrical [3], mechanical [4], and electrochemical properties [5]. These nanomaterials can be dispersed within various matrices, including polymers, ceramics and metals or alloys, allowing for the fabrication of composites with customized properties [6]. Among them, carbon-based 2D materials are especially notable due to their ability to be engineered into different structural forms, such as one-dimensional or 2D configurations, depending on the intended application [7]. This structural flexibility enables their use across a broad spectrum of technological fields.

The application areas of nanomaterial-reinforced composites are diverse. They are widely utilized in energy storage systems [8], sensors [9], electromagnetic shielding materials [10], anti-corrosion coatings [11], biomaterials [12] and thermal insulation solutions [13]. Their outstanding characteristics —such as high surface area excellent electrical conductivity, and superior mechanical strength— [14], make them ideal candidates for next-generation advanced materials [15]. As research progresses, the role of 2D nanomaterials in enhancing the performance and durability of composites is expected to become even more significant, supporting their widespread adoption in various industrial and technological sectors.

Synthetic or artificial leather is a material that can be used instead of leather in different applications such as clothing, footwear, upholstery (car, home and office) and accessories [16]. Artificial leather is also called vegan leather, leatherette, man-made leather, faux leather, pleather, textile leather and imitation leather. However, the term “artificial leather” is used in this work as it is commonly accepted according to European standard EN 15987 [17]. Artificial leather can be commonly used in leather-like finish applications but artificial leather is much cheaper than genuine leather [18]. Artificial leather can be impermeable and waterproof or porous and breathable depending on the structure [19]. The main advantages of the artificial leathers are its lower maintenance cost compared with genuine leather [20].

The surface texture of leather can be formed to resemble leather by decorating it with a grain structure. The common method to obtain

* Corresponding author.
E-mail address: ayavuz@gantep.edu.tr (A. Yavuz).

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artificial leather includes using a casting paper to achieve the required surface finish. This casting paper has the final texture in negative and this paper is coated with polymer to form artificial leather. After the polymer is cured, the paper can be removed and reused. The layer of polymer may include a top layer (having a specific colour), a foam layer, an adhesive layer and a fabric layer. Therefore, artificial leathers generally have textile supports which are covered by several polymer layers.

Two main types of artificial leathers have been produced in the industry: polyurethane [21] or polyvinyl chloride (PVC) [22] based polymers. In this study, PVC based artificial leather has been produced. A plasticizer is a material used to increase plasticity of a substance [23]. Plasticizers are added to a polymer to obtain flexible and softer materials [24]. Plasticizers can be used to decrease the resistance to flow or friction during fabrication process in order to tailor the end products [25]. The brittleness of PVC can be reduced and its softness can be increased by using plasticizers. The mixture of plasticizers (e.g. phthalate) and PVC can be used as artificial leather [26]. The amount of plasticizer can alter the final product. PVC without plasticizers is used in different applications including a window profile and pipes [27]. However, the addition of plasticizers can change the application of PVC including wearable products [28]. The PVC-based artificial leather has low cost and high durability. It can be cleaned easily compared to genuine leather. Artificial leather can be easily colorized and designed.

The properties of polymers can be tailored by modifying their monomer, adding different monomers (copolymerisation) and particles [29]. Alternative methods combining of heat, pressure and catalysis have been researched to obtain new polymers [30]. Nanoparticles have also been added to polymers to change their properties for various applications [31]. Silver nanoparticles were added to PVC for enhancing the antimicrobial properties of the matrix [32]. ZnO nanoparticles have caused the enhancement of dielectric performance of PVC [33]. PVC was synthesised with $CaCO_3$ nanocomposite and their rheological and mechanical properties were reported [34]. Reduced graphene oxide particles have been shown to strengthen mechanical properties of PVC [35]. Electrical conductivity of PVC increased after it was filled with graphene [36].

Carbon nanotubes (single and multi walled) were mixed with PVC in THF solution and prepared by film casting. The electrical conductivity of the PVC matrix increased with increasing CNT's content [37]. The thermal conductivity of the CNT-PVC composite was studied [38]. The effect of carbon nanotubes on the PVC glass transition temperature was reported [39]. The structural, compositional, mechanical, optical, electrical effects of nanoparticles on PVC have been investigated. However, CNT-based PVC has not been commonly used for the large-scale applications. In this study, CNT particles were added to PVC for artificial leather applications.

The main goal of this work is to obtain, characterize and test CNT-filled artificial leathers based on PVC. In this research, the mechanical and chemical properties of neat and CNT-reinforced artificial leathers were studied. The flexibility, abrasion and aging of artificial leathers depending on the addition of CNT to different layers were tested. The chemical and physical properties of PVC-based artificial leather were studied to understand the effects of CNTs with PVC.

2. Experimental details

2.1. Preparation of artificial leather

The transfer coating method was used to obtain CNT-filled PVC-based artificial leather. In this process, the mixture of PVC-based polymer and CNT was poured onto a paper. The transfer paper had a smooth surface to avoid a texture on the artificial leather. Before starting the process, the transfer paper was heated at 200 °C in the machine having a hot air part. PVC was mixed by means of a stirrer with dioctyl terephthalate (DOTP) plasticizers and CNT until a homogeneous-like mixture was obtained. The mixture was left under room conditions for at least 15 min for probable air release. The mixture was spread over the transfer paper to have a thin coating. The viscous mixture on the transfer paper was cured with hot air at 200 °C for 10 s. This process (pouring polymer, spreading and curing) was repeated again for the second layer at 200 °C for an additional 30 s. After the coating of two layers on the transfer paper, the third layer had the same mixture and the lamination of polyester fabric which was also heated at the same temperature in the same oven. Upon coating three layers which had a fabric on the top, the coating was removed from the transfer paper. The transfer paper could be reused for the new formation of artificial leathers. Four different artificial leathers were formed in this study. CNT added PVC is symbolized with “N” and pure PVC with “P” in this work. The codes and PVC types of artificial leather shown in this paper are tabulated in Table 1. The ratio of CNT in the PVC is 0.5 wt%.

2.2. Characterisation of artificial leather

Photo of artificial leather attached to fabric is shown in Fig. 1a. The samples were cut for optical (FTIR and UV), structural (XRD and SEM) and mechanical (tensile, wear and flexibility) characterisation (given in Fig. 1). The samples were cut easily with scissors. The artificial leather could be separated from its fabric. The photos of the background fabric and coating (pure artificial leather) are shown in Fig. 1c and d, respectively. The synthetic leather without its background fabric was used for FTIR and UV characterisation. The size of wear test samples was prepared as 5 cm × 5 cm. The size of the artificial leather to show the flexibility of the samples was 10 cm × 10 cm. Surface morphology of CNT filled and neat PVC-based artificial leather was investigated by Gemini 300 FEGSEM (Zeiss, Germany). The FTIR spectrum of the samples was obtained at a certain wavelength range by means of a Perkin Elmer Frontier spectrometer (Waltham, USA). A Panalytical Empyrean (Malvern, Worcestershire, United Kingdom) X-ray diffractometer having CuKα (1.54 Å) radiation was used between 2θ diffraction angles from 10° to 80° at 6° 2θ min^{-1}.

2.3. Testing of artificial leather

Bending tests were performed under three different conditions: with the backing fabric, without the backing fabric (considering only the artificial leather layer), and following an accelerated aging process. The flexibility of the artificial leather samples was assessed by determining their bending length and flexural rigidity following the procedure outlined in BS 3356:1990, “Standard Method for Measuring the Bending Properties of Fabrics.” In the test procedure, each sample was positioned in a horizontal orientation and permitted to bend naturally under its own weight until its tip made contact with a reference plane. The bending length, measured as the distance from the clamped edge to the point of contact with the reference plane, was recorded. To ensure reliability, each test was conducted three times, and the mean values were calculated.

Two types of artificial leather were evaluated for abrasion resistance in accordance with the BS EN ISO 12947-3 standard. The first type consisted of a PVC coating directly applied onto a textile fabric substrate, referred to as the PVC-coated sample. The second type included a similar textile substrate coated with a composite layer of PVC and CNTs, designated as the PVC + CNT-coated sample. From each material type,

Table 1
neat and CNT-filled PVC materials used in this study.

Code	1st layer	2nd layer	3rd layer
NNN	CNT added PVC	CNT added PVC	CNT added PVC
NPN	CNT added PVC	Neat PVC	CNT added PVC
PNP	Neat PVC	CNT added PVC	Neat PVC
PPP	Neat PVC	Neat PVC	Neat PVC

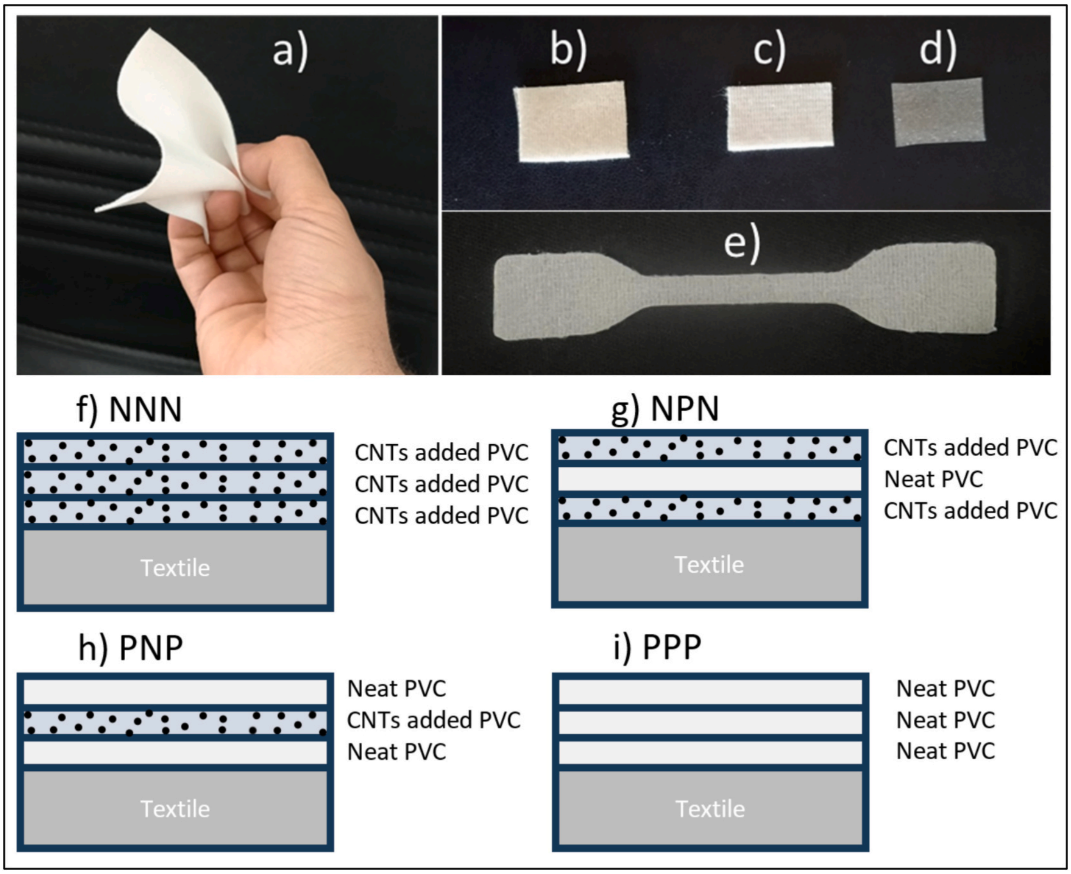

Fig. 1. a) photo of artificial leather attached to background fabric. Artificial leather with fabric used for b) XRD and optical microscopy images. Photograph of c) the fabric and d) pure artificial leather which were separated from each other. Pure leather was used for UV and FTIR analysis. e) photograph of artificial leather with fabric used in tensile test. f-i) Schematic representations of the multilayer artificial leather structures used in this study f) NNN: All three layers consist of CNT-reinforced PVC; g) NPN: Outer and inner layers contain CNT-reinforced PVC, while the middle layer is neat PVC; h) PNP: Only the middle layer is CNT-reinforced, while the outer and inner layers are neat PVC, i) PPP: All three layers consist of neat PVC without CNTs.

three identical circular specimens with a diameter of 38 mm were prepared using a precision die cutter, in compliance with the standard's dimensional specifications. Abrasion resistance testing was conducted using a Martindale abrasion tester. Specimens were subjected to controlled multidirectional rubbing against standard sandpaper (grit size: 180) under a constant load to simulate wear conditions. Each specimen was exposed to a total of 500 abrasion cycles. The abrasive base had a diameter of 140 mm, as prescribed by the standard. Mass loss was determined by weighing each specimen before and after the test using a calibrated analytical balance with a precision of 0.1 mg. Prior to testing, all specimens were preconditioned for 24 h under a standard laboratory atmosphere of 20 ± 2 °C and 65 ± 4 % relative humidity to ensure consistent moisture content.

Tensile tests were conducted to evaluate the mechanical performance of the artificial leather materials. The specimens were cut using a hydraulic press equipped with a custom-designed steel dog-bone mould, ensuring that all samples were prepared with consistent and repeatable dimensions. In order to ensure that the tensile tests reflected only the behaviour of the coating layer, the underlying textile fabric on the backside of the artificial leather was carefully separated. This approach enabled the isolated examination of the effect of CNT incorporation on the mechanical properties by eliminating the influence of the textile-base structure. Thus, tests were performed solely on the polymer or CNT-reinforced composite layers. For each sample group, five replicate tests were conducted to ensure statistical validity. The use of a standardized mould and the removal of the textile backing allowed for reliable assessment of the mechanical properties specific to the coating layers. Tensile tests were performed using a Shimadzu AGS-X universal testing machine with a load capacity of 50 kN. Prior to the main loading phase, the device applied a pre-tensioning step at a rate of 5 mm/min to eliminate slack and ensure proper grip alignment. Subsequently, the main tensile test was conducted at a constant speed of 100 mm/min. The results were evaluated by calculating the average values of maximum tensile strength and strain for each sample group.

3. Results and discussion

Artificial leathers obtained with and without CNT were analysed at the macro level by the naked eyes and a camera presented in Fig. 1a, at the micro level by optical microscope and SEM and at the atomic level by FTIR and XRD. In our study, optical microscopy was employed primarily as an initial, non-destructive technique to examine the surface morphology of the artificial leathers. The choice of optical microscopy was justified by the fact that the artificial leather samples have a multilayered structure, where the top polymer layer forms the visible surface that would directly interact with external factors in real-life applications. Artificial leather was firstly checked by an optical microscope in order to observe any differences due to the addition of CNT. Fig. 2 illustrates the optical micrographs belonging to CNT filled and neat PVC. NNN is the PVC-based artificial leather having CNT addition in its three layers (Fig. 2a) and PPP is the neat PVC-based leather without the addition of CNT (Fig. 2b). Round circles were observed on both images indicating that the effect of CNT addition could not be observed by the optical microscope. PNP and NPN are the other artificial leathers having partly CNT addition in polymer and they are not shown here because all of them indeed had the same structure obtained from

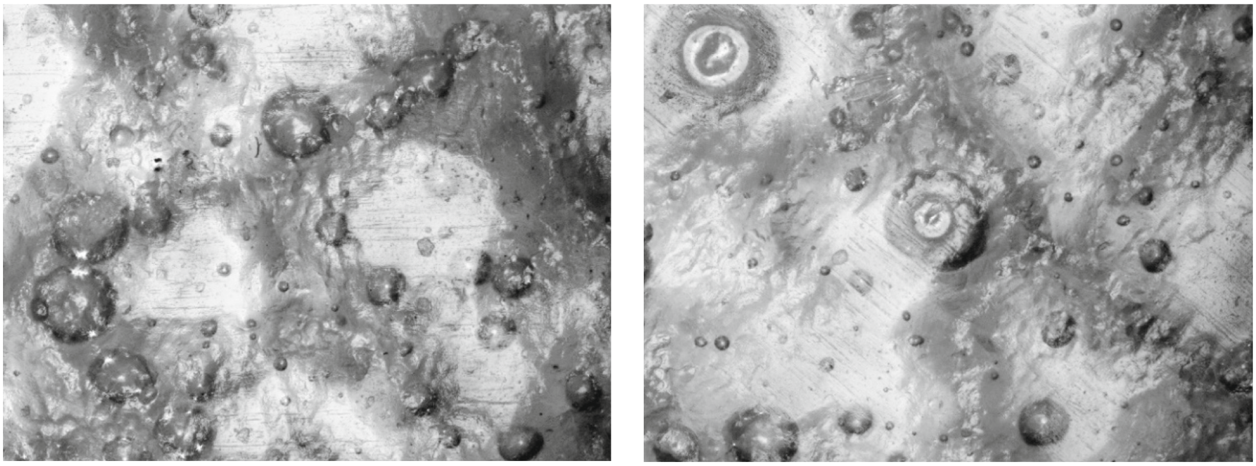

Fig. 2. Optical microscope images of a) CNT-reinforced artificial leather (NNN) and b) undoped artificial leather (PPP), obtained by 100× magnification.

the optical microscope. Only representative images which were PPP and NNN coded artificial leathers are shown here.

SEM is a common technique to observe the surface morphology of materials at high magnification. The CNT addition to the artificial leather was not clarified by the optical microscope. Therefore, SEM images were obtained to examine the effect of CNT on the surface of PVC-based artificial leather. Fig. 3a illustrates CNT before addition to the polymer and three different magnifications of CNT are presented here. Fig. 3a1 and a2 prove the agglomeration of CNT. The nanofiber structure of CNT is observed in Fig. 3a3 as expected. Fig. 3b and Fig. 3c are the SEM images of artificial leather with and without CNT addition, respectively. The surface of PVC-based artificial leather without CNT is smooth (Fig. 3b). However, the morphological structure of PVC-based leather with CNT addition is different (Fig. 3c) from that of neat PVC. Although the addition of CNT was not observed by SEM, the effect of the CNT filler on the PVC surface was observed. It can be deduced from SEM images that the outermost layer of PVC-based artificial leather is a polymer and thus CNT particles could not be observed in the PVC by means of SEM.

The optical microscope was unable to indicate the difference between the surface of CNT doped and undoped PVC because the surface of the coating (PVC based artificial leather) can be detected by an optical microscope rather than the bulk. SEM could not reveal the presence of CNT in the polymer. On the other hand, the effect of CNT on the structure (especially the surface structure) was proven by SEM. UV analysis was conducted to observe the transmittance behaviour of the artificial leathers with and without CNT particles. The UV–Vis spectrum

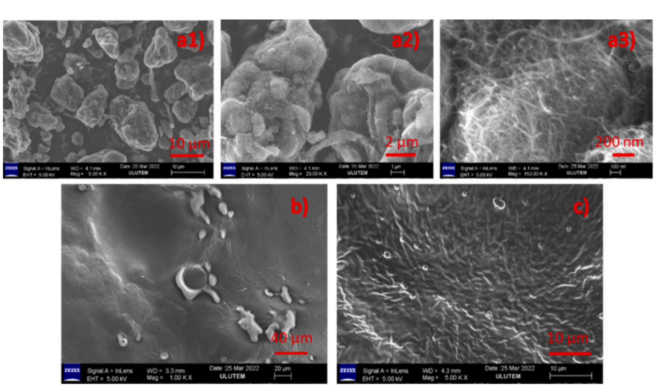

Fig. 3. SEM images of a) CNT; b) undoped artificial leather and; c) CNT-reinforced artificial leather. Panel a illustrates CNT at different magnification.

could show the change of optical behaviour of materials. Fig. 4 illustrates not only the UV results of undoped and CNT doped artificial leather but also the colour change of artificial leather after the addition of CNT. Fig. 4a and Fig. 4b are the images of artificial leather with and without CNT addition, respectively. Although the colour of the neat polymer was yellowish, the colour of CNT added polymer was a darker yellow. Fig. 4a1 and b1 are enlarged images of these polymers. The colour of the neat PVC based artificial leather was homogeneous. However, the colour of CNT doped PVC was not homogeneous because some CNT based particles were not dispersed in the polymer homogeneously. Some of the particles were agglomerated in the polymer which is shown by red arrows in Fig. 4a1. However, the agglomeration of the particles is not significant. The colour of the PVC based artificial leather could easily be changed by adding colouring agents. The fabrication conditions were carefully controlled, and repeated preparation of the undoped polymer consistently yielded a uniform colour. Therefore, the darker coloration observed in the CNT-doped samples is solely attributed to CNT addition. The colour change of the materials could affect the transmittance behaviour. Fig. 4c illustrates the transmittance behaviour of artificial leather with and without CNT. The transmittance of pure artificial leather is greater than that of CNT reinforced leather. The addition of CNT resulted in a decrease in optical transmittance. For instance, at 550 nm, the transmittance of the CNT-doped artificial leather was reduced by approximately 11 % compared to the undoped sample, highlighting the impact of CNT incorporation on the optical properties.

XRD is a technique used to reveal the crystallographic structure of a substance. Materials are irradiated by incident X-rays and the intensities with the scattering angles of the beams leaving the substance can then be measured. The main function of XRD is the identification of substances depending on their diffraction pattern. Additionally, XRD can provide information regarding the actual structure changes depending on the treatments or processes of the material. XRD results of CNT filled PVC (blue line) and neat PVC (red line) are presented in Fig. 5. The XRD pattern of pure CNT is presented in the black line of Fig. 5. The peaks belonging to pure CNT are in good agreement with CNT peaks reported in the literature. XRD patterns of PVC-based artificial leather before and after CNT addition were the same. One could expect that the XRD pattern belonging to CNT doped artificial leather would have CNT peaks. However, this is not the case here because CNT particles were embedded in the bulk of PVC-based polymer. XRD results show that the surface of polymer-based artificial leather was not changed after the CNT particles were added.

XRD of the polymers was obtained by NNN and PPP and these two spectra illustrated that the surface of the polymers either with CNT or

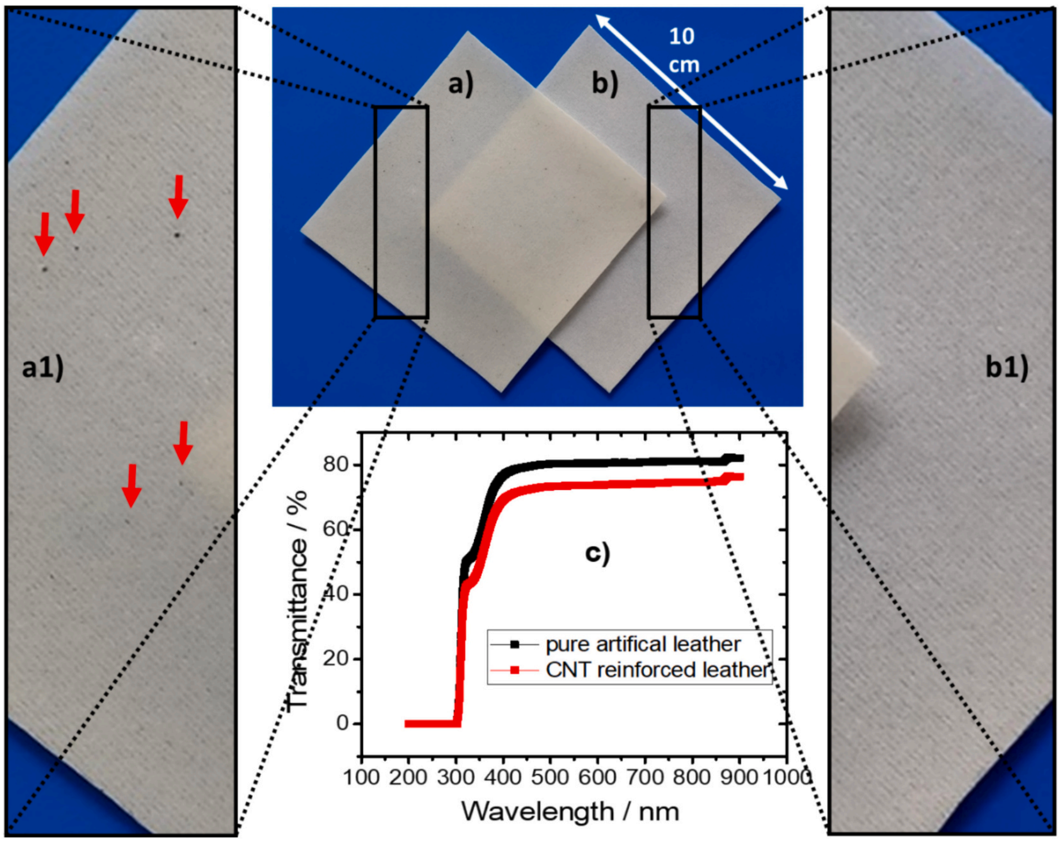

Fig. 4. Photographic image of a) CNT-doped and b) undoped artificial leather. c) UV–Vis spectra of pure artificial leather and CNT-reinforced leather.

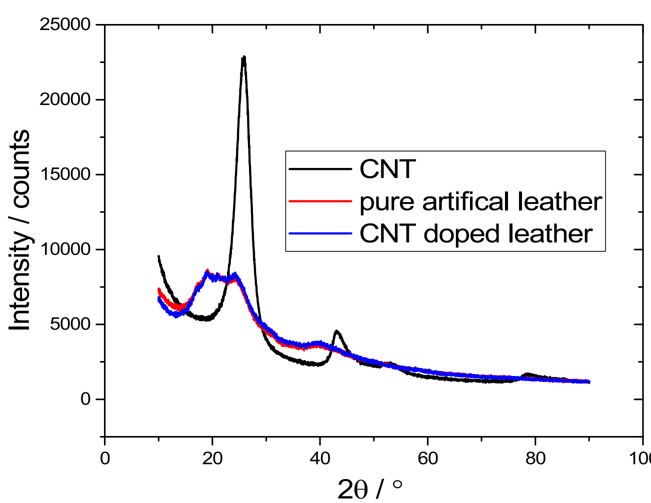

Fig. 5. XRD results of CNT, pure artificial leather and CNT-reinforced artificial leather.

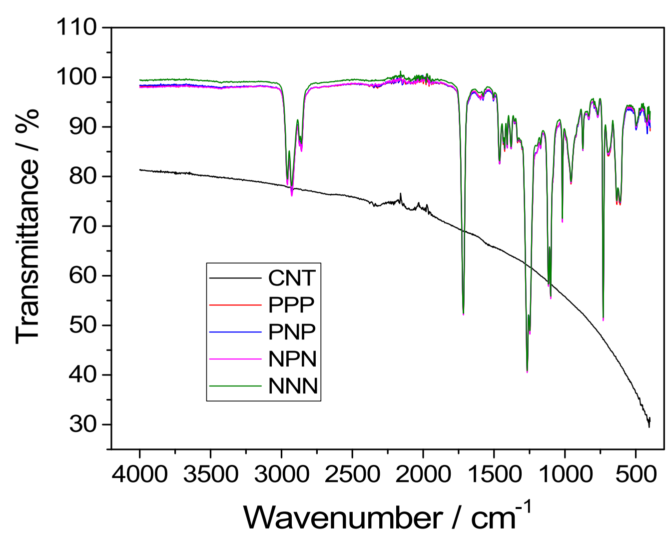

Fig. 6. FTIR spectra of pure CNT, pure artificial leather and CNT-doped artificial leather. P and N represent pure artificial leather and nanoparticle-doped artificial leather, respectively. For example, PNP indicates that the first and third layers are pure polymer (artificial leather), while the second layer is CNT-doped.

without CNT had the same crystallographic structure. FTIR spectrum of NNN, NPN, PNP, PPP and pure CNT is presented in Fig. 6. FTIR result of CNT is different from that of the polymer-based materials. FTIR results of all polymers are the same as each other because the ratio of CNT was less than 1 % and it did not affect the infrared spectrum of absorption or emission of the PVC based polymer. The interaction between the CNTs and the PVC matrix is primarily based on physical adsorption and van der Waals forces, as no chemical functionalization or surface treatment was applied to the CNTs [40,41]. FTIR and XRD results proved that the surface of the artificial leather with or without CNT remains the same, nanoparticles were covered by polymer and nanoparticles cannot directly contact the environment when artificial leather is used in real life.

An accelerated UV aging test was conducted to evaluate the short-term environmental stability of synthetic leather samples with and without CNT reinforcement. The test aimed to provide a preliminary comparison between the materials rather than a comprehensive assessment of long-term durability. The samples were exposed 60 ± 3 °C using

UVA-340 fluorescent lamps. The total exposure time was 168 h. No moisture (condensation or spray) was applied during the test. The test was performed under conditions approximating those specified in ASTM G154, excluding the condensation phase. After the exposure period, both CNT-containing and neat samples exhibited approximately 1 % change in mass (Fig. 7). This variation is likely attributed to surface moisture fluctuations rather than UV-induced degradation. No significant mass loss was detected, suggesting minimal material deterioration under the applied conditions. In terms of colour stability, no noticeable discoloration or little yellowing was observed in the samples. No surface cracking or delamination was detected.

The samples showed increased softness and flexibility following the UV treatment. Initially, the CNT-reinforced synthetic leather exhibited slightly lower flexibility compared to the unreinforced sample. However, after aging, both materials demonstrated comparable tactile softness, indicating that UV exposure may have induced structural relaxation or plasticization in the polymer matrix. UV and thermal exposure did not result in significant degradation in mass, colour, or mechanical feel. The minor changes observed were similar across all material types, suggesting that CNT addition did not significantly alter short-term UV stability under the tested conditions.

The objective of this study was to obtain large-scale CNT doped PVC based artificial leather. CNT particles were added to the mixture of polymer and the process applied for conventional artificial leather was used to fabricate large-scale CNT filled artificial leather. The composite-based leather was left for one hour under room conditions and it was noticed that the flexibility of the artificial leather having CNT particles was different from that of neat artificial leather. Their flexibility behaviour is shown in Fig. 8. PVC based polymer fabrics were cut into 10 cm × 10 cm and they were put on a cylindrical rod to observe their bending. CNT added PVC based artificial leather (coded as NNN) was not bent significantly (shown in the inset of Fig. 8a). However, the polymer consisting of neat artificial leather (coded as PPP) was bent after it was put on the cylindrical rod presented in inset of Fig. 8d. When

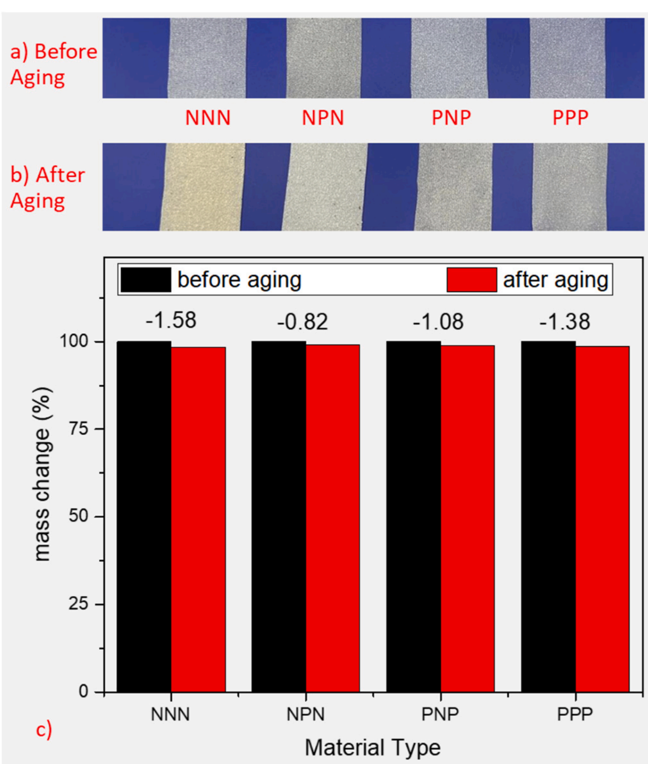

Fig. 7. a) Photographic images of artificial leather samples (NNN, NPN, PNP, PPP) before accelerated aging and b) after aging. (c) Comparison of mass change values for each sample before and after aging.

some layers of the polymers have CNT addition, the bending behaviour was intermediate between neat artificial leather and fully CNT reinforced artificial leather as shown in the inset of Fig. 8b and Fig. 8c. The bending test results, performed according to *BS 3356:1990*, are presented in Fig. 8. The average bending length of the samples with backing fabric decreased from 82 mm for the fully CNT-doped sample (NNN) to 75 mm for the undoped sample (PPP), indicating that the incorporation of CNTs leads to an increase in flexural rigidity. A similar trend was observed in samples without backing fabric, where the bending length decreased from 31 mm to 27 mm. These findings suggest that CNT addition stiffens the artificial leather matrix by restricting its flexibility. After aging, a slight reduction in bending length was observed across all samples, with bending lengths converging to 25–26 mm. This decrease indicates a minor increase in flexibility post-aging, although the effect of CNTs remains noticeable. Overall, the results demonstrate that CNT incorporation enhances the initial mechanical rigidity of the artificial leather, with a moderate softening effect occurring after aging. The observed increase in bending length with CNT addition can be attributed to the influence of nanoparticle dispersion on the macroscopic mechanical behaviour. Dispersed CNTs within the PVC matrix form a reinforcing network that restricts the mobility of polymer chains, thereby enhancing flexural rigidity. This restriction reduces the material's ability to bend under its own weight, resulting in increased bending lengths. This work illustrates that the flexibility of PVC-based artificial leather could be changed significantly when a small amount of nanoparticles (0.5 %) is added during polymerisation. It is known that CNT is still expensive for use in large-scale applications. If a small amount of CNT is added to the products used in daily life, the cost of the materials could be compensated. Although a detailed cost–benefit analysis was not conducted in the present study, previous research has demonstrated that the incorporation of low concentrations of CNTs can significantly enhance the functional properties of polymer-based materials, potentially increasing their service life and reducing maintenance requirements [42,43].

Contact angle measurement can provide information regarding the wettability indicating how a liquid can spread over the artificial leather. The hydrophilic/hydrophobic nature of the artificial leather could be revealed by a water contact angle measurement. The equipment for contact angle measurement uses a water drop. A motorised syringe can be used to deliver distilled water onto the artificial leather. The contact angle between the surface and the water droplet is captured using a camera. Fig. 9 displays water contact angles of undoped and CNT doped artificial leathers. The high-water contact angle on the artificial leather surface can indicate the hydrophilic behaviour of the surface. In samples where CNT-doped layers were present at or near the surface (e.g., NNN), higher contact angles were observed, indicating enhanced hydrophobicity. In contrast, multilayered structures like PNP and NPN, with alternating CNT-doped and undoped layers, exhibited intermediate contact angle values. These results suggest that both the surface composition and the arrangement of underlying layers contribute to the apparent wettability. Therefore, the layered structure was an important factor influencing the contact angle behaviour, as seen in the results presented in Fig. 9. Application of contact angle measurement illustrates less wettability of CNT-reinforced artificial leather. The decrease in hydrophilicity upon CNT addition could be attributed to the non-polar, hydrophobic nature of CNTs, which reduces the surface energy of the composite even when CNTs are embedded within the polymer matrix.

The tensile test results of the artificial leather samples are presented in Fig. 10 and Table 2. The tests were performed on four different sample groups, and both maximum tensile strength and strain values were evaluated. According to the results, all CNT-reinforced samples (NNN, NPN, and PNP) showed higher tensile strength compared to the reference group (PPP), which consisted of only polymer coating. Among them, the NPN sample had the highest average tensile strength at 6.61 MPa, followed by the NNN sample with 5.16 MPa. The PPP sample showed a lower strength of 4.65 MPa. These findings indicate that the

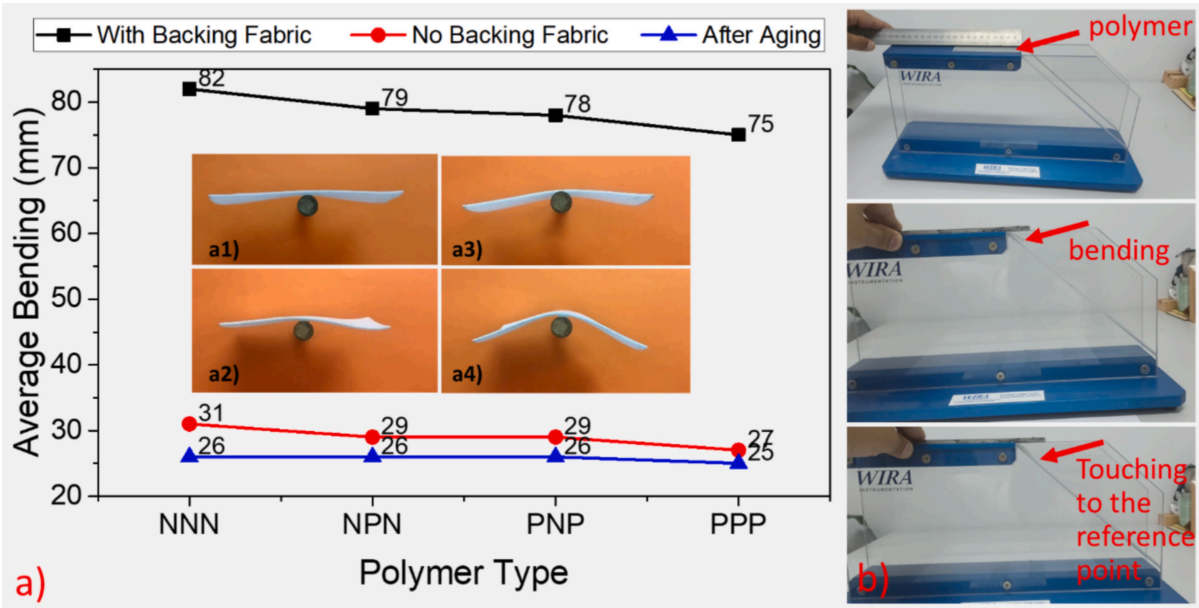

Fig. 8. a) Average bending length of artificial leather samples with and without CNT addition, measured with backing fabric, without backing fabric, and after aging. Inset: photographs of CNT filled PVC-based artificial leather when the layers are a1) NNN (all layers with CNT addition); a2) NPN; a3) PNP and; a4) PPP (neat artificial leather). The artificial leather samples were cut 10 cm × 10 cm. b) photographs of bending test conducted according to BS 3356:1990.

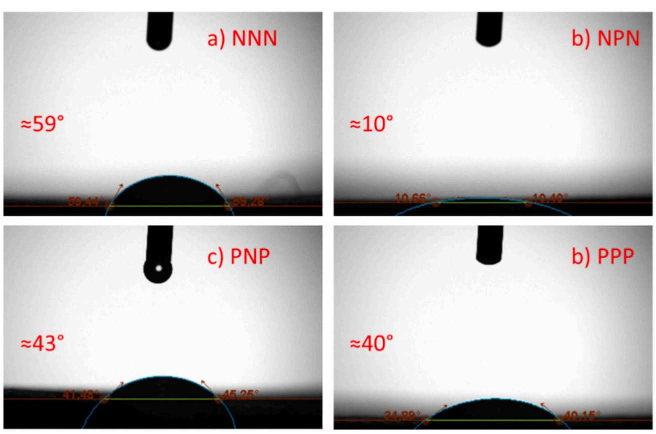

Fig. 9. Water contact angles on a) CNT-added artificial leather (NNN); b) NPN artificial leather; c) PNP artificial leather and d) neat artificial leather (PPP).

addition of carbon nanotubes can improve the mechanical strength of PVC-based artificial leather. This strengthening effect of CNTs in PVC matrices has also been reported in the literature. Akhinaet et al. reported that the incorporation of CNTs into plasticized PVC composites enhanced the tensile modulus, although it significantly reduced elongation at break. They emphasized that the overall mechanical performance is highly dependent on the uniform dispersion of the nanofillers and strong interfacial interactions between the filler and the polymer matrix [44]. Similarly, the enhancement of mechanical performance through the incorporation of CNTs has been widely reported in the literature, where CNTs are shown to improve tensile strength, stiffness, and microstructural stability while suppressing crack propagation under applied stress conditions [45–48].

The stress–strain curves in Fig. 10.a and Fig. 10.b show a steeper initial slope and delayed fracture. This behaviour indicates a higher elastic modulus and improved energy absorption capacity. In addition, Fig. 10.e and Fig. 10.f present a comparative analysis of average tensile strength and elongation values, also including standard deviations that demonstrate the reliability and consistency of the results.

The NNN sample showed the highest average elongation at 180.34 %. The other samples followed in the order of PNP (178.57 %), PPP (175.99 %), and NPN (174.32 %). Although the effect of CNTs on ductility appears limited, the fact that NNN had both higher strength and elongation than PPP suggests a multi-functional reinforcing role of CNTs in PVC-based artificial leather. Overall, these results suggest that CNTs not only enhance tensile strength, but may also contribute to

Table 2
Tensile test results of four artificial leather specimens. Individual values of maximum tensile strength (MPa) and strain (%) from five replicate tests for each material are presented, along with the calculated means and standard deviations (S.D.).

Material	Maximum stress (MPa)						
	1st test	2nd test	3rd test	4th test	5th test	Mean	± S.D.
NNN	5.13	4.70	5.18	5.15	5.65	5.16	0.34
NPN	6.17	6.61	6.81	6.54	6.93	6.61	0.29
PNP	4.96	4.98	4.85	4.72	5.03	4.91	0.12
PPP	4.61	4.79	4.68	4.49	4.67	4.65	0.11
	Strain (%)						
NNN	189.98	167.35	177.63	179.91	186.85	180.34	8.83
NPN	156.71	173.42	185.17	177.20	179.10	174.32	10.72
PNP	168.43	188.85	179.91	168.26	187.42	178.57	9.94
PPP	172.01	191.80	177.24	171.20	167.70	175.99	9.47

better ductility, energy absorption, and resistance to crack propagation in composite materials.

The results of the abrasion tests are presented in Fig. 11.a. Fig. 11.b and Fig. 11.c illustrate coefficient of friction belonging to neat artificial leather and CNT doped artificial leather depending on sliding time under a load of 5 N. The average weight loss was found to be 8.10 % for the PPP samples and 6.02 % for the NNN samples (Fig. 11.a). These findings suggest that the incorporation of CNTs into the PVC matrix may contribute to enhanced abrasion resistance. It is assumed that CNTs act as nanoscale reinforcements within the polymer structure, helping to preserve surface integrity under mechanical stress. Due to their high mechanical strength and excellent thermal conductivity, CNTs may influence the wear behaviour through several possible mechanisms. In particular, previous studies have reported that CNT addition can increase surface hardness, which in turn could provide improved resistance to micro-scratches and surface deformation [49]. Similar observations were also reported in literature [50], where the incorporation of CNTs resulted in reduced wear despite an increase in the coefficient of friction. Their findings align well with the results of this study, further supporting the potential of CNTs to enhance abrasion resistance through mechanisms beyond mere friction reduction.

Moreover, the high thermal conductivity of CNTs is believed to facilitate the dissipation of frictional heat generated during sliding contact, thereby potentially reducing localized thermal softening of the polymer. This could help limit thermally induced surface damage during abrasion [50]. Some reports have also suggested that CNTs might reduce the coefficient of friction due to their ability to impart surface lubricity [51,52]. In such cases, the reduced interfacial shear forces between the material and the abrasive medium could result in lower wear rates. However, the findings of this study do not entirely support that notion. In the tests conducted, the PVC + CNT-coated (NNN) specimens exhibited a slightly higher average coefficient of friction compared to

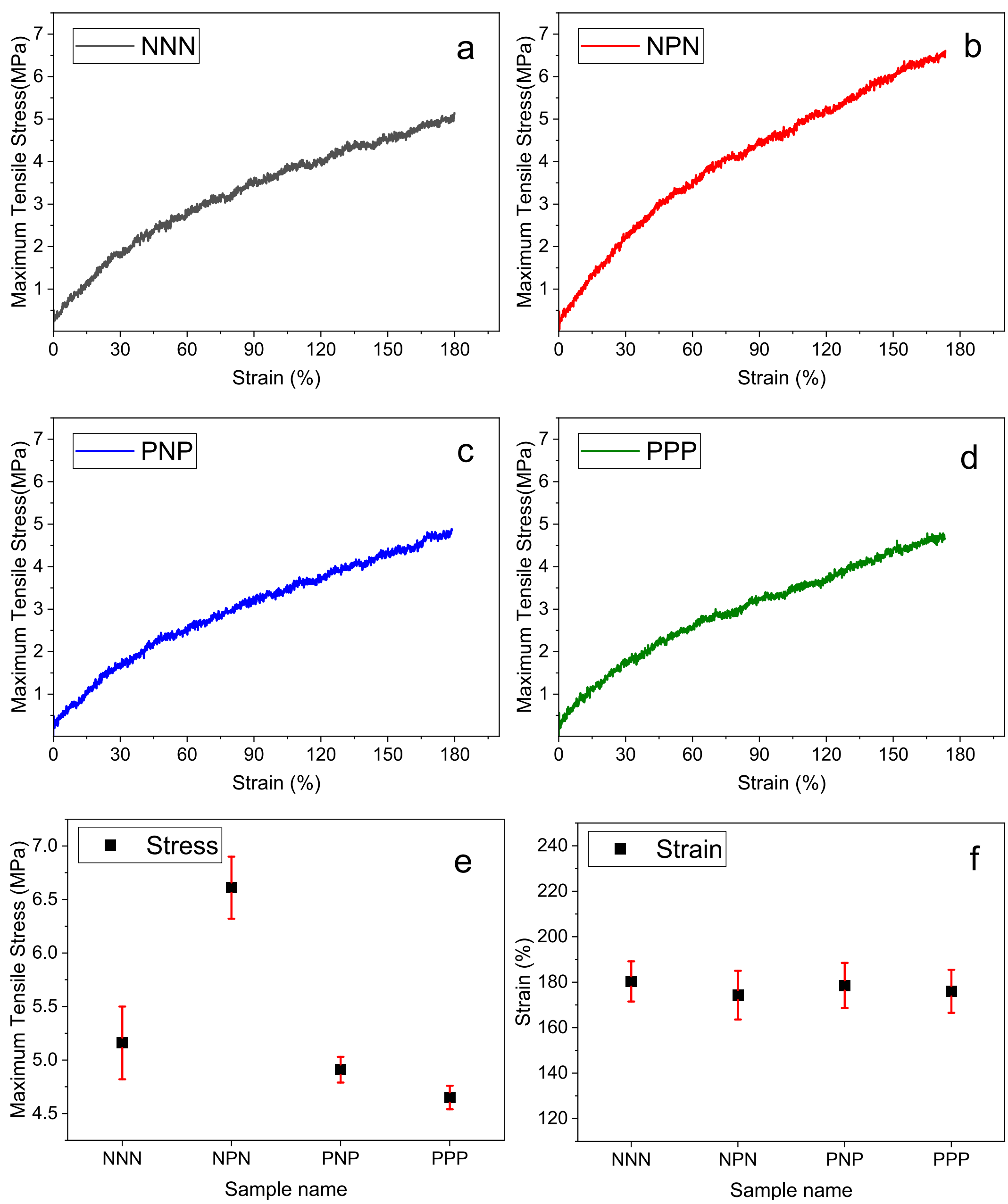

Fig. 10. Representative stress–strain curves of PVC-based artificial leather specimens: (a–c) with CNT reinforcement and (d) without CNT. Comparative bar charts of (e) average maximum tensile strength and (f) average strain for all sample groups, with standard deviation bars included.

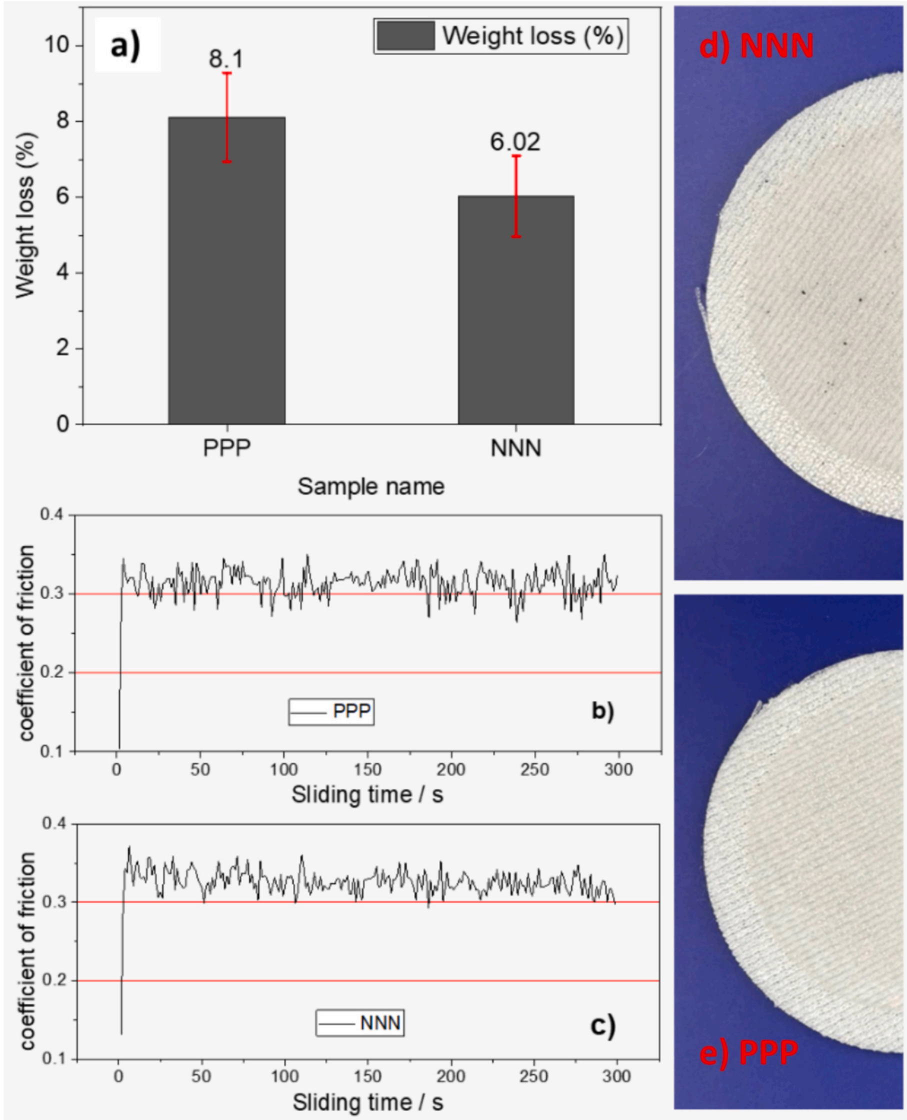

Fig. 11. a) Abrasion test results of two artificial leather samples: PVC-coated (PPP) and PVC + CNT-coated (NNN) showing weight loss percentage with standard deviations after 500 cycles. Relation between sliding time and coefficient of friction for b) neat artificial leather and c) CNT-doped artificial leather. Photographs of d) NNN and e) PPP samples after abrasion testing, highlighting the abraded areas (center) and non-abraded areas (edges).

the PVC-only (PPP) samples. Nevertheless, despite the higher friction, the CNT-containing samples experienced less material loss, indicating better abrasion performance. This observation suggests that the coefficient of friction alone may not be sufficient to predict overall wear behaviour. The improved performance of the CNT-reinforced samples may instead be attributed to a combination of factors, such as increased surface hardness, improved microstructural stability, and more effective thermal management.

Although both material systems exhibited measurable mass loss after abrasion, the significantly lower absolute and relative mass loss observed in the CNT-reinforced specimens underscores the potential effectiveness of CNT incorporation. In addition, the low standard deviations observed in the experimental data support the reliability of the observed differences. Taken together, these results indicate that CNT-reinforced composites may offer greater durability and be better suited for applications that demand enhanced surface wear resistance.

4. Conclusion

CNT doped PVC based artificial leather was produced on a large scale which can be used in daily applications. 0.5 wt% CNT filled PVC based artificial leather was manufactured by the transfer coating method. The mixture of PVC based polymer with CNT particles was poured onto a paper three times and heated by hot air. The last layer had the lamination of polyester fabric and the coating was stripped from the transfer paper. The artificial leather was separated from its fabric for UV and FTIR analysis. The samples were prepared for structural (XRD and SEM) and mechanical (wear and flexibility) characterisation. The effect of CNT addition was not observed by the optical microscope as the microstructure of CNT doped and undoped PVC was similar. SEM was used to find the effect of CNT on the surface of PVC-based artificial leather at the nano level. Before the addition of nanoparticles, the agglomeration of CNT was observed. The surface of neat artificial leather was smoother than that of CNT doped artificial leather. However, CNT particles were not directly observed in PVC based artificial leather because the outermost layer of PVC based artificial leather was a polymer which encapsulated CNT particles. The colour and transmittance behaviour of PVC based artificial leather were changed after the addition of CNT. Neat PVC based artificial leather was homogeneous. Although, CNT doped PVC was not homogeneous because some

CNT particles were agglomerated in the polymer, the agglomerated particles were not significant. The crystalline structure of neat artificial leather was similar to that of CNT doped artificial leather because the XRD peaks belonging to pure CNT were not found as CNT particles were covered completely with PVC based polymer. When CNT particles were added to different layers, the flexibility of the PVC could be changed. CNT added PVC based artificial leather was not easily bent. However, the neat artificial leather was bent. The wettability of the polymers was measured by the water contact angle. The water contact angle of neat artificial leather was less than that of the CNT-doped one. Water contact angle of the composite additionally related to the CNT addition of each layer. The friction coefficient of neat artificial leather was slightly greater than that of CNT added artificial leather. The accelerated aging test was conducted to assess the environmental durability of CNT-doped and undoped PVC-based artificial leather. The results indicate that all samples exhibited minimal colour change after aging, suggesting good stability under simulated environmental conditions. The tensile and abrasion test results demonstrated that the incorporation of CNTs into PVC-based artificial leather significantly enhanced its mechanical performance. Tensile tests revealed that CNT-reinforced samples (NNN, NPN, and PNP) exhibited higher tensile strength compared to the neat PVC sample (PPP), with NPN achieving the highest strength (6.61 MPa). Although CNT addition had a limited effect on ductility, the NNN sample showed both increased strength and elongation, suggesting a multifunctional reinforcing effect. Abrasion tests showed that CNT-reinforced samples experienced lower weight loss (6.02 %) compared to the neat samples (8.10 %), indicating enhanced wear resistance. Overall, the results suggest that CNT reinforcement improves both mechanical strength and durability, making CNT-filled artificial leather a promising candidate for applications requiring enhanced mechanical and surface properties.

CRediT authorship contribution statement

Abdulcabbar Yavuz: Writing – review & editing, Data curation, Validation, Investigation, Writing – original draft. **Musa Yilmaz:** Validation, Investigation, Writing – review & editing, Methodology. **Necip Fazil Yilmaz:** Project administration, Conceptualization, Methodology, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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