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Porous micro-/nano-fibrous silver-coated polymeric scaffolds with tunable mechanical properties for wound healing applications

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Abstract
Electro-spun scaffolds of poly(glycerol sebacate/poly(ε-caprolactone)(PGS/PCL) poly(methyl methacrylate)–poly(ε-caprolactone)(PMMA/PCL) have been using for biomedical applications of tissues engineering due to their attractive thermal, optical, and mechanical properties. In this work, we fabricate both nano-/micro-fibrous scaffolds from a hybrid material composite of PMMA/PCL and PGS/PCL fiber using a standard electro-spinning method and coat one side of the scaffolds with silver nanoparticles (AgNPs). This method of AgNPs coating prevents the scaffold (substrate) from melting behavior, and AgNPs coating reduces the pore diameter and increases fiber diameter, which improves their thermo-mechanical properties. Thereafter, we compare the mechanical properties of pristine PGS/PCL scaffold polymers; PMMA/PCL polymers with the AgNPs-coated PGS/PCL, PMMA/PCL scaffolds. The PMMA/PCL composite fibrous scaffolds show a higher modulus (E), tensile strength (TS), and lower tensile strain without any post-processing. These AgNPs-coated composite fibrous scaffolds provide potential applications in biomedical research fields, such as in fabricating of surgical meshes, bandages, and Band-Aids. Further, the enhanced antibacterial activities of AgNPs, which are used as a coating to our hybrid composite scaffolds, contribute to wound healing.

Keywords Fibrous scaffold · Electro-spinning · Silver coating · Tensile modulus · Composite

Extended author information available on the last page of the article

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Introduction

Chronic wounds and burns are becoming more difficult to resolve issues, and it has been increasingly one of the major public health issues. Recent studies show that more than 5 million patients are contrived by chronic wounds in the USA itself [1, 2]. Skin is the largest organ in humans, many important biological functions, and acts as the primary protecting layer against environmental pathogens. When the skin's barrier is breached, the chances of microbial infections are increased [3–5]. The infections hinder wounds against bacterial infections, which can be favorably taken care of through the use of wound dressings by fabricated AgNPs-coated composite fibrous scaffolds due to their antimicrobial activity of AgNPs [6, 7].

Previously, natural polymers (gelatin, collagen) and their nano-composites have been used for biomedical applications [8–10]. A nano-composite of gelatin containing silver nanoparticles was proposed as a potential material for antibacterial applications. It was observed that the nano-composite gel has antimicrobial effects on a diversified of bacteria strains, such as E. coli, S. aureus, and B. cereus [11, 12]. The Gram-positive pathogens show more significant antibacterial activity than Gram-negative pathogens. The metal nanoparticles were used as additive materials for wound/burn dressings to inhibit microbial activity [13, 14], but they showed less efficient than silver nanoparticles, because these materials do not have foldable behavior, which is required for the effective application of wound dressings. In this regard, synthetic polymers scaffold plays a vital role to stand wound dressing due to their high degree of foldable behavior and biocompatibility. In addition, synthetic polymers offer desirable higher mechanical properties than hydrogel materials. Electro-spun scaffolds possess good morphological features, making them excellent material for tissue engineering, and wound healing applications [15, 16].

Recently, PGS was reported a prospective biopolymer in the development of scaffold hybrid materials for biomedical industrial applications due to its unique thermo-mechanical and biological properties [17–20]. The functional groups of PGS polymer have also been approved by the FDA [20–23] and PGS elastomeric polymer has been attracted as a significant biopolymer because of its easy synthesis process. This polymer has higher biodegradability and biocompatibility, and it has identified as a promising polymer material candidate for tissue engineering industrial applications [24–33]. Recently, some studies have found that PGS/PCL composite-based scaffolds showed great cellular response in several biocompatibility testings. However, recent studies also claimed that pristine PGS polymer, with low molecular weights, is not suitable candidate for the electro-spinning fabrication process. The methodology procedure and formation of PGS nanofibers could however be achieved by addition of other polymer materials such as gelatin or poly(3-caprolactone) (PCL) and polymethyl methacrylate (PMMA). PCL and PMMA polymers and their functional groups are FDA approved. These biodegradable hydrophobic polymers have been exhibited poor cell attachment due to their hydrophobicity property. PGS, PCL, and PMMA show unique physical properties, due to their novel material properties. In addition, we speculate that scaffold coatings by AgNPs, which have significant antibacterial activity, should enhance the antimicrobial activity of fabricated composite scaffold to inhibit bacterial colonization in wound healing applications. Thus, the synthesis or fabrication process of a micron-sized fibrous scaffold having with silver nanoparticles and possessing desirable thermo-mechanical characteristics is of great importance in biomaterial industry [34–44]. Previously, nano-coatings of antibacterial or antimicrobial composite materials, such as metal nanoparticles, and antibiotics on the nano-composite of micro-/nano-fibrous scaffolds have been shown a great potential activity to minimize microbial infections. But the release of nano-coating on the scaffold shows safety concerns, due to their possible toxicity [45–47]. However, microbial infections are common problems associated with medical surgeries and wound healing treatment. It is important to design a scaffold fibrous material with antibacterial agent coating for many tissue engineering and wound healing applications. In this context, we put our focus on investigating the promise of the composite scaffolds with an antibacterial activity, which can better function as tissue engineering skin grafts for wound and burn treatment.

In this work, we fabricated PGS/PCL, PMMA/PCL composite scaffold samples by the electro-spinning process. These nano-composite scaffolds are found to be stable without any further post-processing treatment [33]. The 1:1 ratio of PGS/PCL showed better mechanical properties compared to other reported combinations [48–51]. We coat the scaffolds with silver nanoparticles AgNPs on the surface of fiber scaffolds and measure their thermal, mechanical, and compositional activity. We find the AgNPs coating on the surface of the scaffold enhances their mechanical properties, viscoelastic properties, and thermal stability and acts as desirable antibacterial agents for biomedical applications [52–56].

Methods and characterization

Materials

The chemicals (e.g., PGS, PCL, and PMMA) and solvents (chloroform, ethanol) were purchased from Sigma-Aldrich. Chemical structures of PGS, PCL, and PMMA are shown in Fig. 1. Then the PGS and PCL, PMMA, and PCL blends were dissolved with 1:1 in chloroform: ethanol (9: 1) solution. The concentration of polymer 20% (w/v) is used, and enough time (about 10 h) was allowed for the solutions to mix properly at normal room temperature to get a homogeneous mixture before the electro-spinning process.

Mechanical characterization

The mechanical characteristics were measured using DMA 800 system (TA instrument) at a rate of 1 mm/s, keeping system at room temperature with a 5-N load cell. For the measurements of tensile strength, we used standard ASTM-D 882 technique,

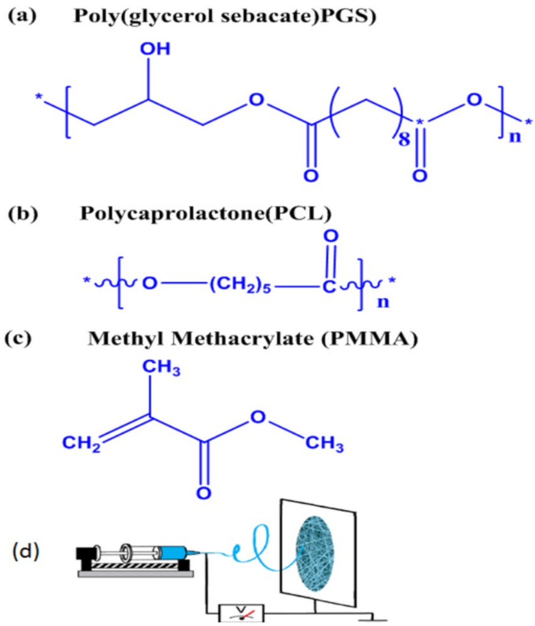


Fig. 1 Molecular structure of **a** PGS, **b** PCL, and **c** PMMA representing the ester bonds and alkaline groups. **d** Schematic of typical electro-spinning design

which has been calibrated with testing of plastic sheets and thickness of less than 0.25 mm.

Thermal analysis

Differential scanning calorimetry (DSC-204 Netzsch) is used to measure heat capacity and the heating/cooling behavior of scaffolds at a heating rate of 3 °C/min.

Thermogravimetric analysis (TGA-209F-Netzsch) is used to measure thermal stability of AgNPs-coated scaffolds under atmospheric N_2 over a temperature range of 27‾800 °C at a heating rate of 3 °C/min.

Microstructure characterization

The details of morphology of hybrid composite fibrous scaffold were carried out using the scanning electron microscopy (HR-SEM-Nova Nano 630).

Fourier transform infrared spectroscopy (FTIR)

The chemical compositions and their functional groups in nano-composite fibrous scaffold were recorded using a Fourier transform infrared spectroscopy (FTIR-6700 ranging from 4000 to 400 cm^{-1}.

Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)

The activity of Ag^+ ions in deionized water (DI) was measured by a Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) to know details of Ag^+ ions release as a part of their antibacterial activity.

Results and discussion

In this work, we used the electro-spinning method (Fig. 1) to make micro-/nano-fibrous scaffold of PGS/PCL (1:1), PMMA/PCL and then coated with 150-nm-thick silver nanoparticles layer (AgNPs) in a controlled method using RF sputtering procedure. The electro-spinning technique is used to make microcomposite scaffolds, and it does not require any further post-processing process. The main challenge during the sputtering of AgNPs coating on the surface of scaffolds is not to increase the substrate temperature (which may likely happen because of the incidence of AgNPs on the scaffold surface, converting the kinetic energy of NPs to heat energy). PCL-based composite scaffolds have a glass transition below 60 °C, and the polymer can melt during the fabrication process if the substrate temperature was not properly controlled. In our procedure, we controlled substrate temperature, which was maintained below 40 °C to avoid any PCL polymer melting. The AgNPs showed better adhesion to the polymer which aids to improve the thermo-mechanical properties of scaffold. The mechanical properties of scaffold materials rely on the microstructure of the scaffold and AgNPs coating. The benefit of RF sputtering over other techniques is to control the exact thickness of AgNPs coating on the scaffolds. In this study, along with the fabrication of AgNPs coating nano-composite scaffolds of PGS/PCL and PMMA/PCL, we focused on the comparison of their thermo-mechanical properties with other reported nano-composite scaffolds. It is expected that AgNPs coating acts as an antibacterial agent for Band-Aid, elastic heaters, strain gauges, temperature sensors, and flexible electronic applications. However, it is important to study different functional groups on the scaffolds to understand the structure of AgNPs-coated fibrous scaffolds.

The FTIR analysis was probed to study the chemical compositions of fibrous composite scaffolds (Fig. 2). All of the functional groups of PGS and PMMA

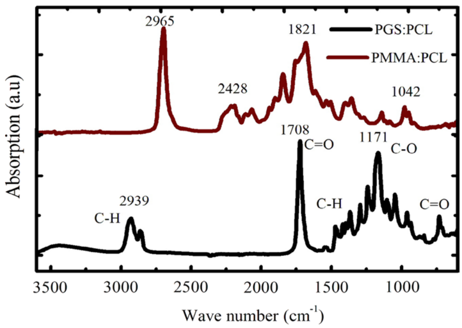


Fig. 2 FTIR spectra of the fibrous scaffold of PGS/PCL and PMMA/PCL

polymers overlapped with PCL polymer bands. Two primary bands were assigned at 1723 cm^{-1} corresponding to stretching vibration of carboxyl (C=O) and 1167cm^{-1}, attributed to stretching vibration of the ether group (C–O) in the spectrum [51]. Other stretching bands were also observed, such as symmetric C–H stretching at 2926 cm^{-1}, C–O, and C–C stretching vibrations at 1295 cm^{-1}. Methyl groups were also stretching [51] C–H at 1360, 2930, 2860 cm^{-1}, and the ester band C–O vibration was observed at 1166, 1723, 930, and 1287 cm^{-1}. FTIR revealed that PGS, PCL, and PMMA polymer characteristics were still present, even though polymers were greatly reduced in their microstructure. The scaffold films are thin enough, and their functional characteristics of polymers can still hold surface-active materials.

The surface morphology of both fibrous scaffolds is shown in Fig. 3. The diameter and porosity of the scaffold play a vital role in improving mechanical characteristics of the scaffold. The Ag coatings (150 nm thick) on the surface of scaffold fiber improve mechanical characteristics due to reduction of pore size, increasing diameter, and stronger interfacial interactions between the scaffold fiber and silver nanoparticles, Fig. 4. The diameter of pristine scaffolds was measured as 400 nm using statistical analysis of the normal distribution of SEM images with the help of ImageJ software, Fig. 5. The diameter of pristine fibrous scaffolds increases and pore size decreases after AgNPs coating on scaffolds.

The mechanical characteristics were measured using a fibrous scaffold with and without silver nanoparticles (AgNPs) coating. Both fibrous scaffolds were used for mechanical measurements having rectangular shape and an average thickness of 100–200 μm. In Fig. 6A, the imbedded figure shows the linear region of the stress–strain curve for both scaffolds in 10–15% strain range. The mechanical characteristics of scaffolds depend on their microstructure parameters such as fiber

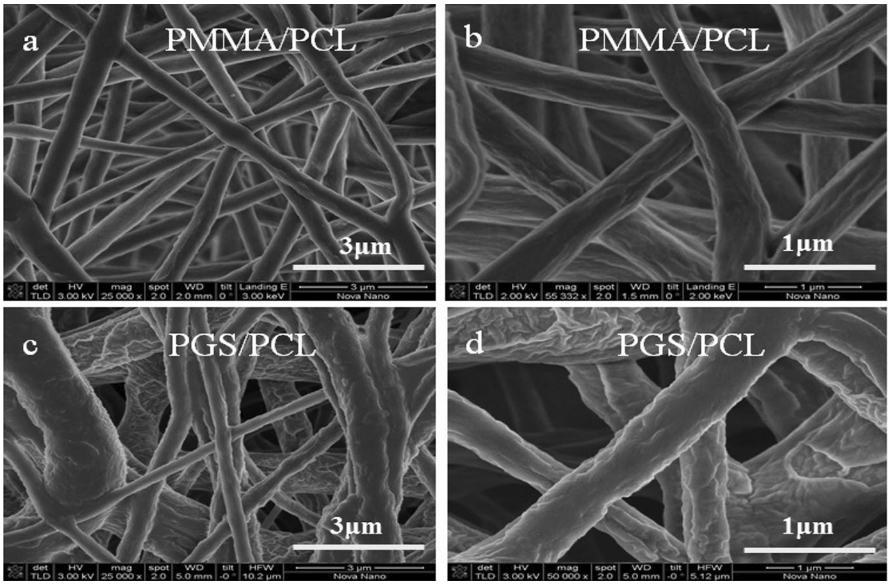


Fig. 3 SEM images of the pristine fibrous of **a**, **b** PGS/PCL and **c**, **d** PMMA/PCL scaffolds

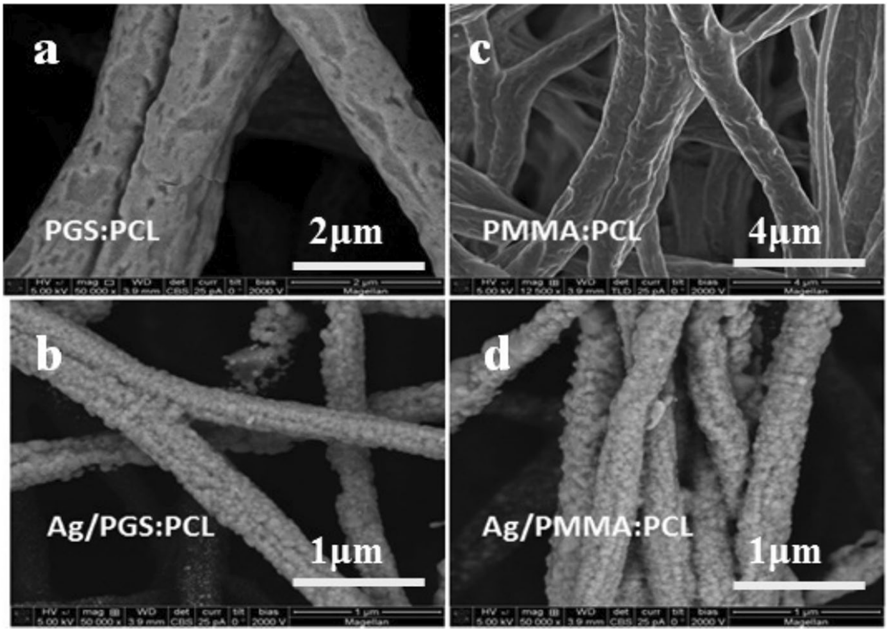


Fig. 4 SEM images of the pristine fibrous **a** PGS/PCL, **c** PMMA/PCL scaffold and AgNPs-coated fibrous scaffolds, **b** 150-nm AgNP-PGS/PCL, **d** 150-nm AgNP-PMMA/PCL

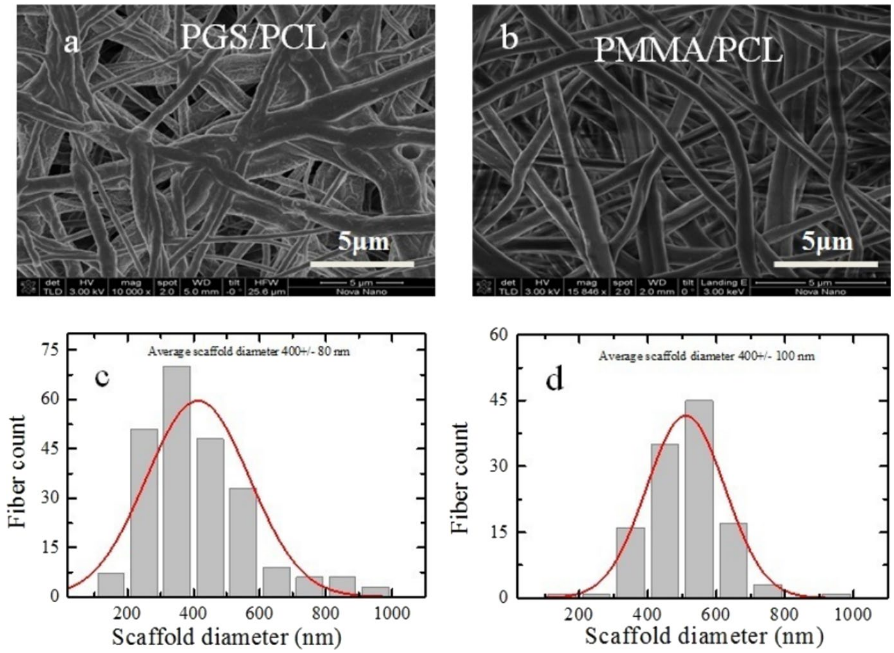


Fig. 5 SEM images of the pristine fibrous **a** PGS/PCL, **b** PMMA/PCL scaffolds. Pristine fibrous scaffold distribution of diameter **c** PGS/PCL and **d** PMMA/PCL

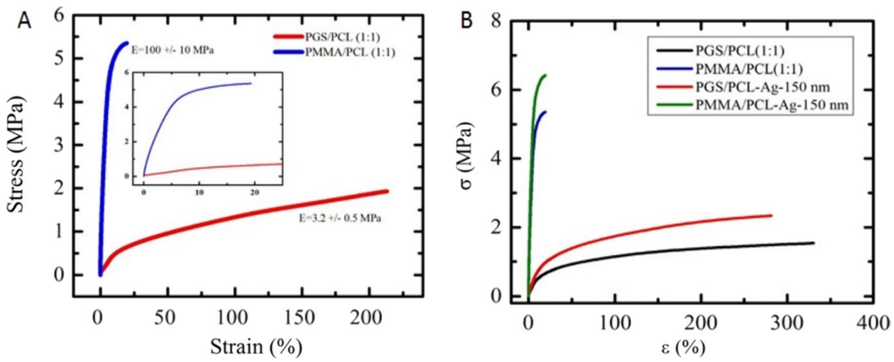


Fig. 6 **A** The tensile stress (σ) versus tensile strain (ϵ) of fibrous scaffold of PGS/PCL and PMMA/PCL, **B** the tensile stress (σ) versus tensile strain (ϵ) of the fibrous scaffold of Ag-coated PGS/PCL and PMMA/PCL

diameter, pore diameter, and outer coating of metal. The tensile modulus of pristine PGS/PCL (1:1) scaffolds showed about 3.3 MPa, whereas PMMA/PCL showed about 100 MPa. The mechanical properties of AgNPs-coated scaffolds increase 3–4 times higher than the pristine scaffolds, Fig. 6B.

The pristine ultimate tensile strength (UTS) of PMMA/PCL scaffold showed approximately 30 times higher compared to the pristine PGS/PCL polymer scaffold. Interestingly, the tensile strain increased about 250% for PGS/PCL scaffold, whereas PMMA/PCL scaffold showed only 25% strain (Fig. 6B). The AgNPs coating on scaffold may help to make brittle scaffold due to stronger interfacial interaction between AgNPs and scaffold fiber. The PMMA/PCL fibrous scaffold showed higher degree of modulus (E), higher UTS, and higher stiffness compared to PGS/PCL fibrous scaffold due to tightly packed morphological structure with higher diameter (Fig. 2C). The morphological stretching of the scaffold fiber after mechanical testing is shown in Fig. 7. The PGS/PCL scaffold fiber showed

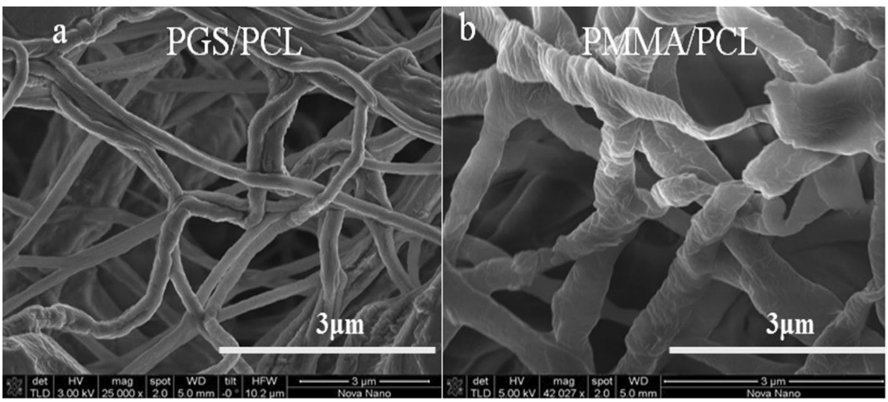


Fig. 7 SEM images of the pristine fibrous PGS/PCL and PMMA/PCL scaffolds after mechanical testing

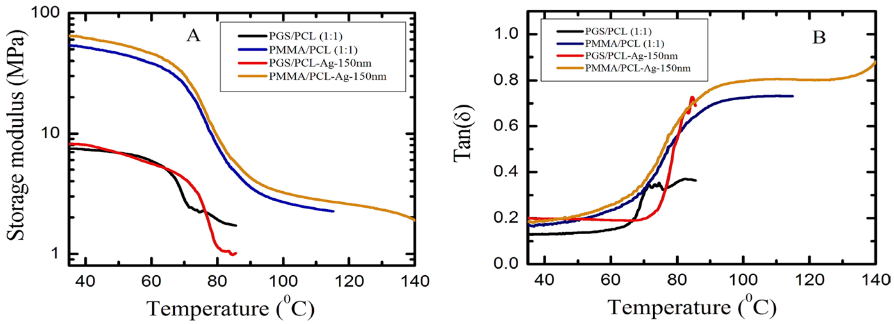
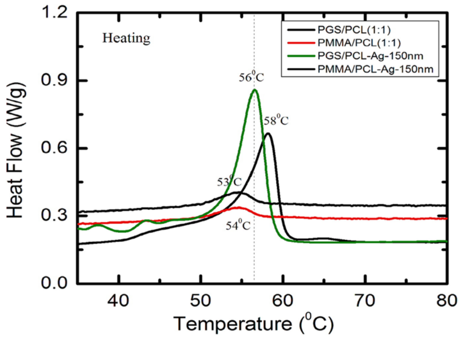


Fig. 8 **A** The storage modulus is a function of temperature measurements for both PGS/PCL and PMMA/PCL scaffolds, **B** damping ratio (tan δ) versus temperature measurements for both PGS/PCL and PMMA/PCL scaffolds

Fig. 9 Differential scanning calorimetry measurements of pristine and Ag-coated fibrous scaffold of PGS/PCL, PMMA/PCL



a twisting and stretching behavior after mechanical stretching, whereas PMMA/PCL scaffold showed lower twisting and tape-type stretching behavior. As a result, one should note that PMMA/PCL scaffold is a good material for expanded wound healing applications. We speculate that the primary cause behind scaffolds greatly improved mechanical properties after AgNPs coating is the increased friction between the fibers. It might also be due to the interlocking of fibers, which avoids any slippage, and increases the friction between adjacent fibers which is observed more on the surface of fiber.

The Ag coating induced restricted thermal motion of micro-scaffold fiber through the altering melting and glass transition temperature of fiber. We assessed the melting transition temperature and their glass transition of both fibrous scaffolds using DMA technique (Fig. 8). The glass transition temperature of both pristine fibrous scaffolds showed a broader glass transition temperature 60–90 °C. The storage modulus (E') of PMMA/PCL & Ag-PMMA/PCL showed much higher values than PGS/PCL & Ag-PGS/PCL fibrous scaffold (Fig. 8A) due to the heat transfer between the fibers and the AgNPs coating. Both pristine scaffold samples started fracturing at a lower temperature due to the melting of fibers, whereas the mechanical fracture of Ag-coated scaffold was shifted

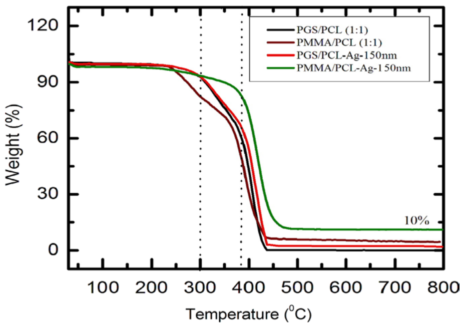


Fig. 10 Thermogravimetric analysis (TGA) measurement was taken for both pristine PGS/PCL, PMMA/PCL scaffolds and Ag-coated PGS/PCL, PMMA/PCL scaffolds under nitrogen atmosphere. The mass loss in fibers associated with burning fibrous scaffolds was reduced in Ag-coated scaffolds

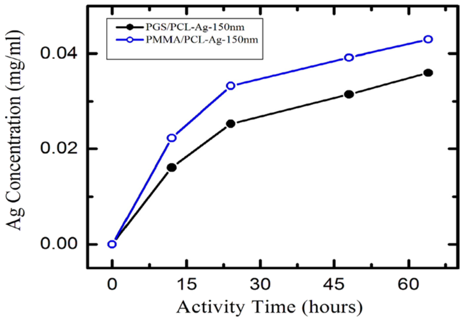


Fig. 11 Cumulative release of Ag+ ion concentration of Ag-coated fibrous PGS/PCL and PMMA/PCL scaffolds in DI water as a function of time using ICP-OES

to a higher temperature, suggesting that Ag acted as a strong antibacterial agent (mechanical integrity) to the pristine scaffold. The Ag coating restricts the fiber motion, leading to increased stiffness of the scaffolds, resulting in their mechanical reinforcement.

The origin of the mechanical improvement of fibrous scaffolds and Ag-coated scaffolds was assessed using differential scanning calorimetry (DSC). We examined scaffold crystalline behavior and stiffness, both of which would lead to enhancing modulus (E) and lower melting temperature (T_m). Our analysis showed a sharp melting peak at 58 °C (Fig. 9), and the melting temperature for both scaffolds showed a reduction in the temperature of about 2 °C. The endothermic peak slightly increased for Ag-coated fibrous scaffold which suggests an increased crystalline behavior due to the restricted thermal motion of microfibers and micro-/nano-confinement of Ag coating. The glass transition temperature of the micro-fibrous scaffold was broad and close to the melting temperature from DSC and was analyzed from DMA measurements.

We also examined both fibrous scaffold's thermal stability using TGA technique shown in Fig. 10. The mass degradation of fiber in Ag-coated fibrous scaffold associated with burning off was reduced. The mass degradation of Ag-coated scaffolds was probably decreased because of heat transfer from silver nanoparticles to fibers which led to stronger interfacial interaction. The mass loss of scaffolds showed two regimes which might be because of the degradation of the temperature of two polymers that phase separate before they degrade completely. The thermal stability of both Ag-coated scaffolds was seen to be improved about 10 °C. The Ag-coated sample left 10% weight even at 800 °C, and it might be due to the nano-confinement of Ag coating on micro-scaffold composites.

We emphasize that silver nanoparticles are a potential candidate for wound healing due to their antibacterial activity. The concentration of Ag^+ ions releases from the scaffolds needed to be identified. The release of Ag^+ ions from Ag-coated fiber scaffolds was investigated by the total immersion method in DI water media to investigate the antibacterial activity. The Ag-coated scaffolds were in DI water (2 ml) for several days before that concentration of Ag^+ ions was measured by ICP-OES (Fig. 11). The release profile of Ag^+ ion for both Ag-coated scaffolds was found to show similar trends (Fig. 10). We estimated that approximately 5–10% of AgNPs were released even after 3 days. The amount of AgNPs coating on the fiber surface was observed to be significantly high even after 3 days of activity, and we compared the coating levels before studying their activity. We suggest that the controlled release of Ag^+ coating from both scaffolds prevents possible toxicity while processing antibacterial activity on these scaffolds. Therefore, we highlighted Ag-coated scaffolds hold great potential promise in many biomedical applications such as a wound healing dressings, surgical meshes, and antibacterial sutures.

Conclusion

In this work, we fabricated silver nanoparticles (AgNPs) and coated composite fibrous scaffolds of PGS/PCL and PMMA/PCL using the electro-spinning technique and RF sputtering. By utilizing RF coating method, we successfully fabricated uniform coating on the surface of the electro-spun blend of PGS/PCL and PMMA/PCL polymers. The FTIR technique presented that the PGS, PCL, and PMMA polymer features in the composite scaffold were not entirely lost although the structure was greatly changed. This indicates the polymer scaffold does not change chemical characteristics and surface activity. The mechanical characteristics of scaffolds were improved probably because of the increased friction between fibers after Ag coating. We believe that the reason for the enhancement in mechanical characteristics by adding such nano-coating is due to the intermeshing of fibers. The coating prevents slippage and increases frictional forces between adjoining fibers on top of each other. We speculate that these fibers lost less mass due to the heat transfer of Ag+ coating, which improved the thermal stability of scaffolds. We used AgNPs coating on the scaffolds to enhance the antibacterial activity and control the release of Ag^+ ions on the surface of the scaffolds, observing that the release of Ag+ ions was steady with the time and did not vary for any of the AgNPs-coated scaffolds. We highlighted that the AgNPs coating on the surface of scaffolds provides potential applications such as surgical meshes, bandages, and possible antibacterial activity in wound healing and, finally, emphasize that many metal nanoparticles were used as additive materials for wound dressing to inhibit microbial activity, but they were less efficient than silver nanoparticles, because these materials do not have foldable behavior which is required for effective applications of wound dressings. In this regard, AgNPs coating on the surface of PGS/PCL, PMMA/PCL composites scaffolds provides higher mechanical properties with desirable biomedical applications.

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Declarations

Conflict of interest There are no conflicts to declare.

References

1. Sen CK, Gordillo GM, Roy S, Kirsner R, Lambert L, Hunt TK, Gottrup F, Gurtner GC, Longaker MT (2009) Human skin wounds: a major and snowballing threat to public health and the economy. Wound Repair And Regen 17(6):763–771
2. Atiyeh BS, Costagliola M, Hayek SN, Dibo SA (2007) Effect of silver on burn wound infection control and healing: review of the literature. Burns 33(2):139–148
3. Driver VR, Fabbi M, Lavery LA, Gibbons G (2010) Erratum: the costs of diabetic foot: The economic case for the limb salvage team (Journal of Vascular Surgery (2010) 52: 3 SUPPL.(17S-22S)). J Vasc Surg 52(6):1751
4. Branski LK, Gauglitz GG, Herndon DN, Jeschke MG (2009) A review of gene and stem cell therapy in cutaneous wound healing. Burns 35(2):171–180
5. Singer AJ, Clark RA (1999) Cutaneous wound healing. N Engl J Med 341(10):738–746
6. Bayram Y, Parlak M, Aypak C, Bayram İ (2012) Three-year review of bacteriological profile and antibiogram of burn wound isolates in Van. Turk Int J Med Sci 10(1):19
7. Kanmani P, Rhim JW (2014) Physicochemical properties of gelatin/silver nanoparticle antimicrobial composite films. Food Chem 148:162–169
8. Zhang L, Jiang Y, Ding Y, Daskalakis N, Jeuken L, Povey M, O'Neill AJ, York DW (2010) Mechanistic investigation into antibacterial behaviour of suspensions of ZnO nanoparticles against E. coli. J Nanopart Res 12:1625–1636
9. Arfat YA, Benjakul S, Prodpran T, Sumpavapol P, Songtipya P (2014) Properties and antimicrobial activity of fish protein isolate/fish skin gelatin film containing basil leaf essential oil and zinc oxide nanoparticles. Food Hydrocolloids 41:265–273
10. Kalakonda P, Banne S (2018) Synthesis and optical properties of highly stabilized peptide-coated silver nanoparticles. Plasmonics 13:1265–1269
11. Kalakonda P, Sreenivas B (2017) Synthesis and optical properties of highly stabilized peptide-coated gold nanoparticles. Plasmonics 12:1221–1225
12. Kalakonda P (2016) Synthesis of silver nanowires for highly conductive and transparent films. Nanomater Nanotechnol 6:1847980416663672
13. Hemar Y, Liu LH, Meunier N, Woonton BW (2010) The effect of high hydrostatic pressure on the flow behaviour of skim milk–gelatin mixtures. Innov Food Sci Emerg Technol 11(3):432–440
14. Sheu MT, Huang JC, Yeh GC, Ho HO (2001) Characterization of collagen gel solutions and collagen matrices for cell culture. Biomaterials 22(13):1713–1719
15. Kong HJ, Wong E, Mooney DJ (2003) Independent control of rigidity and toughness of polymeric hydrogels. Macromolecules 36(12):4582–4588
16. Khademhosseini A, Vacanti JP, Langer R (2009) Progress in tissue engineering. Sci Am 300(5):64–71
17. Radisic M, Park H, Martens TP, Salazar-Lazaro JE, Geng W, Wang Y, Langer R, Freed LE, Vunjak-Novakovic G (2008) Pre-treatment of synthetic elastomeric scaffolds by cardiac fibroblasts improves engineered heart tissue. J Biomed Mater Res Part A 86(3):713–724
18. Redenti S, Neeley WL, Rompani S, Saigal S, Yang J, Klassen H, Langer R, Young MJ (2009) Engineering retinal progenitor cell and scrollable poly (glycerol-sebacate) composites for expansion and subretinal transplantation. Biomaterials 30(20):3405–3414

19. Kalakonda P, Aldhahri MA, Abdel-Wahab MS, Tamayol A, Moghaddam KM, Rached FB, Pain A, Khademhosseini A, Chaieb S (2017) Microfibrous silver-coated polymeric scaffolds with tunable mechanical properties. RSC Adv 7(55):34331–34338
20. Kalakonda P, Banne S (2017) Thermo-mechanical properties of PMMA and modified SWCNT. Composites. Nanotechnol Sci Appl 10:45
21. Kalakonda P, Banne S, Kalakonda PB (2022) Study of mechanical anisotropy of single walled carbon nanotube and polyvinyl alcohol polymer nanocomposite with a controlled alignment process. J Polym Res 29(10):442
22. Masoumi N, Larson BL, Annabi N, Kharaziha M, Zamanian B, Shapero KS, Cubberley AT, Camci-Unal G, Manning KB, Mayer JE, Khademhosseini A (2014) Electrospun PGS: PCL microfibers align human valvular interstitial cells and provide tunable scaffold anisotropy. Adv Healthc Mater 3(6):929–939
23. Wang Y, Ameer GA, Sheppard BJ, Langer R (2002) A tough biodegradable elastomer. Nat Biotechnol 20(6):602–606
24. Wang Y, Kim YM, Langer R (2003) In vivo degradation characteristics of poly (glycerol sebacate). J Biomed Mater Res Part A 66(1):192–197
25. Fidkowski C, Kaazempur-Mofrad MR, Borenstein J, Vacanti JP, Langer R, Wang Y (2005) Endothelialized microvasculature based on a biodegradable elastomer. Tissue Eng 11(1–2):302–309
26. Sundback CA, Shyu JY, Wang Y, Faquin WC, Langer RS, Vacanti JP, Hadlock TA (2005) Biocompatibility analysis of poly (glycerol sebacate) as a nerve guide material. Biomaterials 26(27):5454–5464
27. Khademhosseini A, Langer R, Borenstein J, Vacanti JP (2006) Microscale technologies for tissue engineering and biology. Proc Natl Acad Sci 103(8):2480–2487
28. Motlagh D, Yang J, Lui KY, Webb AR, Ameer GA (2006) Hemocompatibility evaluation of poly (glycerol-sebacate) in vitro for vascular tissue engineering. Biomaterials 27(24):4315–4324
29. Catledge SA, Clem WC, Shrikishen N, Chowdhury S, Stanishevsky AV, Koopman M, Vohra YK (2007) An electrospun triphasic nanofibrous scaffold for bone tissue engineering. Biomed Mater 2(2):142
30. Engelmayr GC Jr, Cheng M, Bettinger CJ, Borenstein JT, Langer R, Freed LE (2008) Accordion-like honeycombs for tissue engineering of cardiac anisotropy. Nat Mater 7(12):1003–1010
31. Gao J, Crapo P, Nerem R, Wang Y (2008) Co-expression of elastin and collagen leads to highly compliant engineered blood vessels. J Biomed Mater Res Part A 85(4):1120–1128
32. Boland ED, Pawlowski KJ, Barnes CP, Simpson DG, Wnek GE, Bowlin GL (2006) Electrospinning of bioresorbable polymers for tissue engineering scaffolds. American Chemical Society, Washington
33. Baker BM, Gee AO, Metter RB, Nathan AS, Marklein RA, Burdick JA, Mauck RL (2008) The potential to improve cell infiltration in composite fiber-aligned electrospun scaffolds by the selective removal of sacrificial fibers. Biomaterials 29(15):2348–2358
34. Balguid A, Rubbens MP, Mol A, Bank RA, Bogers AJ, Van Kats JP, de Mol BAJM, Baaijens FPT, Bouten CV (2007) The role of collagen cross-links in biomechanical behavior of human aortic heart valve leaflets—relevance for tissue engineering. Tissue Eng 13(7):1501–1511
35. Kim GH (2008) Electrospun PCL nanofibers with anisotropic mechanical properties as a biomedical scaffold. Biomed Mater 3(2):025010
36. Li C, Vepari C, Jin HJ, Kim HJ, Kaplan DL (2006) Electrospun silk-BMP-2 scaffolds for bone tissue engineering. Biomaterials 27(16):3115–3124
37. Balguid A, Mol A, van Marion MH, Bank RA, Bouten CV, Baaijens FP (2009) Tailoring fiber diameter in electrospun poly (ε-caprolactone) scaffolds for optimal cellular infiltration in cardiovascular tissue engineering. Tissue Eng Part A 15(2):437–444
38. Almajhdi FN, Fouad H, Khalil KA, Awad HM, Mohamed SH, Elsarnagawy T, Albarrag AM, Al-Jassir FF, Abdo HS (2014) In-vitro anticancer and antimicrobial activities of PLGA/silver nanofiber composites prepared by electrospinning. J Mater Sci Mater Med 25:1045–1053
39. Chaubey N, Sahoo AK, Chattopadhyay A, Ghosh SS (2014) Silver nanoparticle loaded PLGA composite nanoparticles for improving therapeutic efficacy of recombinant IFNγ by targeting the cell surface. Biomater Sci 2(8):1080–1089
40. Selcan Gungor-Ozkerim P, Balkan T, Kose GT, Sezai Sarac A, Kok FN (2014) Incorporation of growth factor loaded microspheres into polymeric electrospun nanofibers for tissue engineering applications. J Biomed Mater Res Part A 102(6):1897–1908

41. Jiang J, Xie J, Ma B, Bartlett DE, Xu A, Wang CH (2014) Mussel-inspired protein-mediated surface functionalization of electrospun nanofibers for pH-responsive drug delivery. Acta Biomater 10(3):1324–1332
42. Wang H, Li Y, Jiang S, Zhang P, Min S, Jiang S (2014) Synthesis, antimicrobial activity, and release of tetracycline hydrochloride loaded poly (vinyl alcohol)/soybean protein isolate/zirconium dioxide nanofibrous membranes. J Appl Polym Sci 131(20):40903
43. Tseng YY, Liu SJ (2015) Nanofibers used for the delivery of analgesics. Nanomedicine 10(11):1785–1800
44. Kalakonda P, Kalakonda PB, Banne S (2021) Studies of electrical, thermal, and mechanical properties of single-walled carbon nanotube and polyaniline of nanoporous nanocomposites. Nanomater Nanotechnol 11:18479804211001140
45. Kalakonda P, Cabrera Y, Judith R, Georgiev GY, Cebe P, Iannacchione GS (2015) Studies of electrical and thermal conductivities of sheared multi-walled carbon nanotube with isotactic polypropylene polymer composites. Nanomater Nanotechnol 5:2
46. Kalakonda P, Daly M, Xu K, Cabrera Y, Judith R, Iannacchione GS, Georgiev GY, Cebe P (2013) Structure-electrical transport property relationship of anisotropic iPP/CNT films. MRS Online Proc Libr (OPL) 1499:mrsf12-1499
47. Sant S, Iyer D, Gaharwar AK, Patel A, Khademhosseini A (2013) Effect of biodegradation and de novo matrix synthesis on the mechanical properties of valvular interstitial cell-seeded polyglycerol sebacate–polycaprolactone scaffolds. Acta Biomater 9(4):5963–5973
48. Ifkovits JL, Devlin JJ, Eng G, Martens TP, Vunjak-Novakovic G, Burdick JA (2009) Biodegradable fibrous scaffolds with tunable properties formed from photo-cross-linkable poly (glycerol sebacate). ACS Appl Mater Interfaces 1(9):1878–1886
49. Ifkovits JL, Padera RF, Burdick JA (2008) Biodegradable and radically polymerized elastomers with enhanced processing capabilities. Biomed Mater 3(3):034104
50. Sant S, Hwang CM, Lee SH, Khademhosseini A (2011) Hybrid PGS–PCL microfibrous scaffolds with improved mechanical and biological properties. J Tissue Eng Regen Med 5(4):283–291
51. Qian G, Zhang L, Liu X, Wu S, Peng S, Shuai C (2021) Silver-doped bioglass modified scaffolds: a sustained antibacterial efficacy. Mater Sci Eng, C 129:112425
52. Ferry JD (1980) Viscoelastic properties of polymers. Wiley
53. Flory PJ, Rehner J Jr (1943) Statistical mechanics of cross-linked polymer networks II. Swelling. J Chem Phys 11(11):521–526
54. Landel RF, Nielsen LE (1993) Mechanical properties of polymers and composites. CRC Press
55. Parvathalu K, Kumar DN, Rajitha K, Kishan MG, Kumar BN, Bhemarajam J, Naidu SR, Merlinsheeba GL, Mandal P, Banne S, Dayanand A, Morampudi V, Murali B, Vinodini SEN, Reddy YV, Bhaskar PB (2023) Facile synthesis of silver nanoparticles using green tea leaf extract and evolution of antibacterial activity. Plasmonics 18(5):1837–1845
56. Parvathalu K, Chinmayee S, Preethi B, Swetha A, Maruthi G, Pritam M, Sreenivas B, Naidu SR, Merlinsheeba GL, Murali B, Vijay M, Moses K, Krishna DC, Bhaskar PB (2023) Green synthesis of silver nanoparticles using Argyreia nervosa leaf extract and their antimicrobial activity. Plasmonics 18(3):1075–1081

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