Regenerez®: A Next-Generation Material for Bioresorbable Coatings

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Coatings consisting of natural and synthetic origin play a major role in the world of medical devices both from a functional and a biological perspective. Collagen and similar materials are often used to coat surgical meshes to minimize the formation of intra-abdominal adhesions following hernia repair procedures. Coatings are also applied to cardiovascular grafts to provide a blood-tight structure until the graft is populated with host tissue. A coating made from a material that provides a beneficial mechanical and biological response would be an invaluable asset to medical device engineers. Regenerez®, a bioelastomer made with poly(glycerol sebacate) (PGS) has shown tremendous promise in the field of tissue engineering and regenerative medicine, and it is an ideal coatings candidate due to its elastomeric and cell-friendly properties.1,2

Coating Textiles

To determine the coating properties of Regenerez (PGS), a number of textile structures of various compositions were used as substrates to determine the coating characteristics of PGS. For PGS to adhere to the substrate, the surface energy of the substrate must be similar to the surface energy (tension) of the coating material. Typical materials used in biomedical textiles include polyethylene terephthalate (PET), polyglycolic acid (PGA), polyetheretherketone (PEEK), nitinol (NiTi) and polypropylene (PP). These materials have a broad range of surface energies (mN/m)—PET (44.6)3, PGA (49.6)4, and PEEK (42.1)3—and are theoretically sufficient enough to allow wetting by PGS, which has a surface energy of 42mN/m.5 However, materials such as PP (30.1)3 and PE (35.7)3 exhibit a decreased affinity for PGS and therefore require surface modification prior to coating application.

The coating of the textiles was monitored using scanning electron microscopy (SEM) and the effect on mechanical properties was determined by measuring changes in tensile strength.

Figure 1. Representative SEM images comparing uncoated (A) PEEK, (B) PGA, (C) PET, (D) NiTi textiles to coated (E) PEEK, (G) PET, (H) NiTi textiles. The coating solution consisted of 20% PGS in ethyl acetate.
The method used to coat the materials can either be a standard solvent-based dip-coating or spray-coating process. The micrographs in Figure 1 depict samples of PEEK, PGA and PET that were successfully dip-coated, as well as spray-coated NiTi. Images seen in Figure 2 represent samples of PGS-coated polypropylene before and after surface modification using plasma treatment. A casting method can also be used with these materials to create a film of PGS that encompasses the entire textile structure. The solvent-based coatings and casting methods afford the ability to create films from the micron to the millimeter scale. Whereas the casting method can only be controlled by the amount of PGS casted, the dip and spray methods can regulate coating thickness in multiple ways. One way to control coating thickness is by varying concentrations of PGS in the coating solution. To illustrate the effect of dip-coating concentration, three samples of PET woven mesh were coated with a solution of 10%, 20% and 30% PGS.

In Figure 3, the increase in coating thickness by increasing % solids can be seen by the covering up of the warp yarns from (A) to (C). The sample coated with a 10% solution contains lightly coated PGS filaments, whereas at 30% the filaments are fully coated, and the underlying yarns are completely encased.

In some cases such as spray-coating, increasing the percent solids of the coating solution is not an optional method for increasing PGS film thickness. Another method for building coating thickness is by depositing multiple layers of PGS (see Figure 4). This can be achieved by dip or spray coating one layer, allowing the solvent to evaporate, and reapplying the coating. The process can be repeated with each layer to create a thicker PGS coating. This is a useful method to evenly increase coating thickness without increasing the percentage of PGS in the coating solution.
To form the elastomeric version of PGS, the resulting film must first be cured to impart the desired level of elasticity. As the coating thickness is varied by the methods described above, the resulting cure time also varies. For example, a longer dip time with a higher concentration of PGS will take longer to cure than one layer deposited from a dilute solution of PGS. Therefore, the elasticity of the PGS-coated textile can be tailored by changing cure time. Longer cure times result in a stiffer coating, whereas the minimum cure time produces a more viscoelastic coating. Samples of PET coated in a 30% PGS in ethyl acetate solution were cured in a vacuum oven at 120°C for different lengths of time and Figure 6 depicts the trend of decreasing crystallization temperature with increasing cure times, signifying an increase in PGS crosslink density indicated by an increase in peak load.

Another method for controlling coating thickness is increasing the dip or spray time used in the coating process. Figure 5 shows the effect of using two different dip times, 5 seconds and 2 minutes. The SEM images demonstrate that longer dip times result in increased coating thickness, which is indicated by the increased coverage of the PET yarns.

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Figure 6. Effect of coating cure time on crystallization temperature and peak load.
Strength and Strain Testing

Tensile strength and torsional strain are two parameters used to investigate the mechanical effect imparted by the PGS coating on the textile structures. Tensile tests were performed on samples of uncoated and coated PET woven fabric and PET knitted mesh. Both coated samples were dip-coated using a 30% PGS in ethyl acetate solution for 1 minute. Also, torsional testing was completed on uncoated and coated PET woven ribbon samples prepared under the same conditions as the tensile-tested samples. The MTS tensile tester was used to monitor the effect of the PGS coating on the maximum peak load of the textile.

![Figure 7. Peak Load Data from MTS for Uncoated and Coated PET textiles.](image)

The peak load of an uncoated textile structure will vary depending on its method of construction (Figure 7). However, both structures show an increased peak load when coated with PGS. The PET woven fabric shows roughly an 80% increase in peak load when coated with PGS and the PET knitted mesh shows an approximate 20% increase. The varied effect of the PGS coatings indicates that the peak load increase from the PGS coating is dependent on the textile construct, because both samples were coated under the same conditions but resulted in a different peak load increase. In addition to the increase in peak load of the two PET samples, the failure mechanism also changed when the textile was coated with PGS. The stress-strain curve of the uncoated samples exhibits a saw tooth pattern as the individual filaments break prior to failure. However, the coated samples exhibited no fluctuation prior to failure.

![Figure 8. Representative SEM images of failure point of uncoated PET woven fabric after tensile testing.](image)
The higher storage and loss modulus values for the uncoated woven ribbon indicate the sample is more stiff and rigid compared to the coated sample. For the coated sample, the lower storage and loss modulus values signify that the PGS coating creates a more flexible, viscoelastic material.

Figure 10 depicts an amplitude sweep taken on an uncoated and PGS coated sample of PET woven ribbon. The amplitude sweeps measure storage modulus (solid character) and loss modulus (liquid character) as a function of strain. In this case, the term strain refers to the ratio of the deflection path of the tool to the distance between the two tools, or the sample height. The test is conducted by securing a strip of uncoated or coated textile between two clamps and oscillating to achieve the appropriate percentage of strain. The images of the break point of the coated PET woven fabric show a clean, even break as a result of the PGS binding the multifilament structure into a larger, stronger monofilament structure. Instead of the individual filaments bearing the load separately, the PGS enables the filaments to work together, dispersing the tensile load over a larger area.

The increase in peak load with the PGS coating suggests the PET textile has increased stiffness, however, torsional testing indicates the PGS coating imparts elasticity to the textile. Using a rheometer fitted with a torsional testing apparatus, amplitude sweeps can be performed on samples with mostly solid character. Amplitude sweeps measure storage modulus (solid character) and loss modulus (liquid character) as a function of strain. In this case, the term strain refers to the ratio of the deflection path of the tool to the distance between the two tools, or the sample height. The test is conducted by securing a strip of uncoated or coated textile between two clamps and oscillating to achieve the appropriate percentage of strain. The images of the break point of the coated PET woven fabric show a clean, even break as a result of the PGS binding the multifilament structure into a larger, stronger monofilament structure. Instead of the individual filaments bearing the load separately, the PGS enables the filaments to work together, dispersing the tensile load over a larger area.

Figure 9. Representative SEM images of failure point of coated PET woven fabric after tensile testing.

Figure 10. Amplitude sweep of uncoated (orange) and PGS coated (green) PET ribbon. Triangles and squares represent G" (loss modulus) and G’ (storage modulus), respectively.

The higher storage and loss modulus values for the uncoated woven ribbon indicate the sample is more stiff and rigid compared to the coated sample. For the coated sample, the lower storage and loss modulus values signify that the PGS coating creates a more flexible, viscoelastic material.
In addition, the amplitude sweep data in Figure 10 illustrates the ability of PGS to better maintain the structure of the textile, similar to the effects seen in the tensile testing of the coated sample. This occurrence is represented by the increase of storage and loss modulus around 0.5% strain in the uncoated sample, but not in the coated sample. This event occurs due to the crinkling or the disruption of the uncoated textile structure (Figure 11).

![Figure 11. Images of (A) coated PET woven ribbon, (B) uncoated PET woven ribbon, (C) uncoated PET woven fabric, and (D) coated PET woven fabric after torison testing.](image)

The image of the woven fabric sample in Figure 11 (C and D) shows an uncoated and coated sample that was subjected to an even larger amount of strain than the PET woven ribbon described in Figure 11 (A and B). Consequently, the difference between these two uncoated samples is more drastic, but the coated samples maintain their structure in both examples. Furthermore, the decrease in modulus values seen at higher strains is indicative of the sample reaching its yield strain, or the point in which the structure begins to break down. In the amplitude sweep of the uncoated and coated PET woven ribbon, the storage modulus values of the coated samples remain more linear to higher strain values than the uncoated sample, further supporting that PGS helps to better maintain the textile’s integrity.

**Conclusion**

As the demand for performance and biocompatibility in the medical device space continues to increase, so will the need for devices that are more biologically and physically compliant. Coatings technology provides a bolt-on technology for materials commonly used in medical devices, as they have shown utility in improving the biological and physical properties of finished devices. As a coating, PGS has tremendous potential based on its ability to uniformly coat multiple polymeric materials in a controlled and reproducible manner. As discussed, a Regenerez coating enhanced the mechanical properties of a coated textile by improving the mechanical properties of the coated textile. In addition to improving the mechanical properties of coated textiles, Secant Group is currently investigating the use of Regenerez coatings in improving biological response and its ability to promote tissue regeneration.
References


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