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Hydraulic Seals for a circular Future

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Recycling PTFE-based materials is challenging because mechanical properties degrade when waste material is reintroduced into virgin compounds. In this study, we investigate the incorporation of two PTFE-based recycled materials (repro): a bronze-filled PTFE repro and a mineral fiber-filled PTFE repro, into virgin compounds. Mechanical tests were performed to investigate the effect of repro addition on mechanical properties. Seal performance of the materials was subsequently investigated under severe operating conditions, and friction, leakage, wear and deformation were evaluated. The results reveal a strong dependence of repro incorporation on compound type and microstructural interactions. The Turcon® T46 material showed good tolerance to repro incorporation, and the compound containing virgin PTFE and 66 wt.% bronze-filled PTFE repro showed seal performance comparable or better than the virgin Turcon® T46 compound. The Turcon® M12 material, on the other hand, showed pronounced sensitivity to repro addition, with significant reductions in strength and ductility due to weak interfacial bonding and stress concentration effects associated with larger repro particle size. However, the application of the proprietary repro processing step significantly improved interfacial bonding in the Turcon® M12 system, which then improved both mechanical behavior and seal performance. These findings demonstrate that repro incorporation is governed not only by the repro content but also by the particle size distribution, compound architecture and interfacial bonding. The study also highlights that repro incorporation must be tailored to the specific compound and that combining mechanical testing with seal testing is essential for developing high-performance repro sealing materials that do not compromise mechanical and tribological performance.

1 Introduction

Fluoropolymers are macromolecules that play an important role in modern life [1]. Thanks to their attractive properties, such as chemical and thermal stability, they are used across many industries, including automotive, aerospace, marine, mining, medical, waterproof coatings, sealings, fuel cells and membranes for the Li-ion batteries [1], [2]. Polytetrafluoroethylene (PTFE) is a semi-crystalline, high-performance polymer that held largest volume share of the global fluoropolymer market in 2025 [1], [2], [3], [4]. A low coefficient of friction, high thermal stability, high flexural strength, good chemical compatibility, dielectric properties and hydrophobicity are just some of the properties that make PTFE a perfect material for sealing applications [5]. However, PTFE suffers from low wear resistance. The poor wear resistance is usually improved by adding different fillers [6], [7]. Various filler reinforcements are used, such as bronze, carbon black, carbon fibers, mineral fibers, glass fibers, graphite, molybdenum disulfide and different polymer materials [6], [8], [9], [10]. These fillers improve wear performance and mechanical stability, but they also introduce additional complexity to the material system, particularly in the context of recycling.

Unlike other thermoplastics, PTFE cannot be processed using conventional methods [2], [11]. Its high viscosity in the molten state hinders the use of injection molding or hot extrusion [2]. Instead, PTFE seal parts are produced through a three-stage process of compression molding, sintering and machining. The sintering process changes the physical properties of the final product, such as elongation, tensile strength and residual stresses [2]. It is precisely the state of the PTFE after sintering, together with the presence of different fillers, that hinders PTFE recycling. As a result, a significant amount of PTFE waste, especially from the machining process, ends up in landfill [5], [12]. The wide range of PTFE applications, the PFAS restriction proposal, the lack of good-enough alternatives to PTFE, uncertainty regarding PTFE availability in Europe and considerable pressure from society regarding PTFE's potential environmental hazards have all intensified initiatives for PTFE recycling technologies [5], [13], [14]. Furthermore, strict governmental policies, together with the circularity and emissions reduction targets of manufacturers of PTFE-based products, stimulate the development of recycling technologies with a lower environmental impact and improved economic feasibility [15], [16]. Trelleborg Sealing Solutions has established a strategic circularity objective to integrate 25% recycled or bio-based content by 2030, driving innovation in the more resource-efficient processing of PTFE for hydraulic sealing applications.

PTFE turning operations traditionally generate substantial amounts of waste. Yet the chemical stability and re-processable nature of PTFE allow finely ground PTFE waste to be reintroduced into compounds through mechanical or primary recycling [5]. This approach involves collecting, sorting and grinding sintered PTFE waste into a powder (repro) and reintroducing it into the original product cycle [11], [13]. The process lets the sintered material be reused, although its physical properties differ from those of virgin PTFE, reduces the need for new raw materials and lowers environmental impact [5]. However, the incorporation of repro into virgin high-performance polymers such as PTFE is often limited by deterioration in mechanical and tribological properties [5], [16]. Two limiting behaviors can be distinguished when incorporating repro. Repro particles may act as a structural continuation of the matrix, where good interfacial bonding between the repro and the material matrix enables effective stress transfer and preserves mechanical integrity of the material. Alternatively, repro particles may behave as defects or features that induce stress concentrations, which, combined with weak interfacial adhesion to the matrix and their large particle size, promote debonding and crack initiation [9].

This work demonstrates that recycled PTFE is not inherently bad for the sealing performance. However, repro particle size, interfacial bonding and the type of material matrix (virgin PTFE material versus filled PTFE compound) are critical parameters affecting overall material performance.

2 Experimental methods

2.1 Materials and compounding

The materials investigated in this study were based on recycled PTFE compounds (compounds with repro) and corresponding virgin compounds (virgin matrices). The virgin PTFE compounds Turcon® T46 and Turcon® M12 used in the study are offered by Trelleborg Sealing Solutions for different sealing applications, with which we have gained extensive experience over the past decades. The virgin Turcon® T46 compound, is a high-grade composition of virgin PTFE compounded with Turcon® and bronze, while the virgin Turcon® M12 compound, is a high-grade composition of virgin PTFE compounded with Turcon®, mineral fiber and additives. Throughout this article, the Turcon® T46 and Turcon® M12 virgin compounds are denoted as T46 and M12, respectively.

Three repro systems were evaluated, differing in filler type, filler content and repro particle size characteristics.

- T46 repro with a particle size in the range of 40 to 80 µm

  The T46 repro compound was created by blending T46 virgin compound with a 25 wt.% T46 repro loading. This compound is denoted as T46_R25 throughout this article.

- Bronze-filled PTFE repro with a particle size in the range of 40 to 80 µm

  The bronze-filled PTFE repro was blended at 66 wt.% into a virgin PTFE matrix. This repro compound corresponds to the formulation of T46 compound with 66 wt.% repro and for clarity is denoted as T46_R66 throughout this article.

- M12 repro with a particle size in the range of 100 to 150 µm

  The M12 repro compounds were created by blending M12 virgin compound with multiple M12 repro loading levels (0-20 wt.%). Compared with the T46 repro, the particle sizes of the M12 repro were larger. The milling energy needed to mill the M12 compound and obtain a reduced particle size of M12 repro would be significantly higher than that needed for milling the T46 compound. Furthermore, preliminary trials showed excessive heat generation in the impact mill. Therefore, within the scope of this work, a particle size comparable to that of the T46 repro was not considered for the M12 repro. A proprietary in-house process for handling large M12 particles after air classification was used to improve the interfacial bonding between larger M12 repro particles and the M12 virgin compound. The M12 compound containing 15 wt.% repro and the M12 compound containing 15 wt.% repro subjected to the proprietary in-house processing step were exposed to mechanical and seal testing and are hereafter denoted as M12_R15 and M12_PR15, respectively.

2.2 Material processing

The bronze-filled PTFE compound, virgin T46 and virgin M12 turning wastes were processed separately using an impact mill. The milled repro was afterward classified using an air classifier. The classifier controlled the cut-off particle size and the proportion of removed particles. The desired particle size distribution was tailored by combining and identifying optimal impact mill and classifier settings.

2.3 Material testing

To investigate and demonstrate the effect of repro incorporation on mechanical and tribological properties of the PTFE compounds, mechanical and seal performance tests were carried out.

2.3.1 Mechanical testing

Mechanical testing and evaluation of mechanical properties (tensile strength and elongation) were performed on an Instron tensile tester (Bluehill Universal Instron 5965). Specimens for mechanical testing were prepared from batch billets by cutting 0.75 ± 0.05 mm thick discs, from which dog-bone shaped specimens were stamped according to the ASTM D 4894 standard for all M12 repro systems mentioned above. On the other hand, the mechanical properties of the three bronze-filled PTFE systems (T46, T46_R25 and T46_R66), were determined using specimens obtained by turning 1.5 ± 0.2 mm thick bushings from the tubes, followed by stamping dog-bone shaped specimens according to the ASTM D 4894 standard. All specimens were stretched at a 50 mm/min strain rate until they broke, and the measurements were repeated five times. All measurements were performed at ambient temperature (approximately 23 ºC) in the test laboratory. Bluehill Universal software was used to calculate the mechanical properties of the different material blends: tensile stress (strength) at break and tensile strain (elongation) at break.

Mechanical testing served as an initial screening tool to verify whether the investigated repro loadings are suitable for subsequent dynamic sealing evaluation.

2.3.2 Performance testing

Performance testing of the materials, carried out on the Trelleborg test rigs, included Stepseal® tribological evaluation for selected blends. Dynamic sealing performance was evaluated using a reciprocating seal test rig. The Stepseal® test specimen (a single sealing element) was installed in a housing with a radial clearance of 0.6 mm and operated against a Ø50 mm hard chrome-plated rod (Cromax) under a constant hydraulic pressure of 300 bar. Tests were conducted in mineral oil (Equivis ZS 46, Total Energies), and the fluid temperature was maintained at 55 °C, measured in the oil tank. Reciprocating movement was imposed with a stroke length of 280 mm at a running velocity of 0.2 m/s. The test ran for 200,000 cycles, corresponding to a total running distance of approximately 112 km.

The sealing tests were conducted under these severe conditions, specifically chosen to challenge material performance and enable clear differentiation between material systems.

3 Results and discussion

3.1 Influence of bronze-filled PTFE repro on the mechanical properties of the repro compounds

In Figures 1 and 2 present the tensile stress and tensile strain at break, respectively, for the T46, T46_R25 and T46_R66 compounds with repro particle size in the range of 40 to 80 µm.

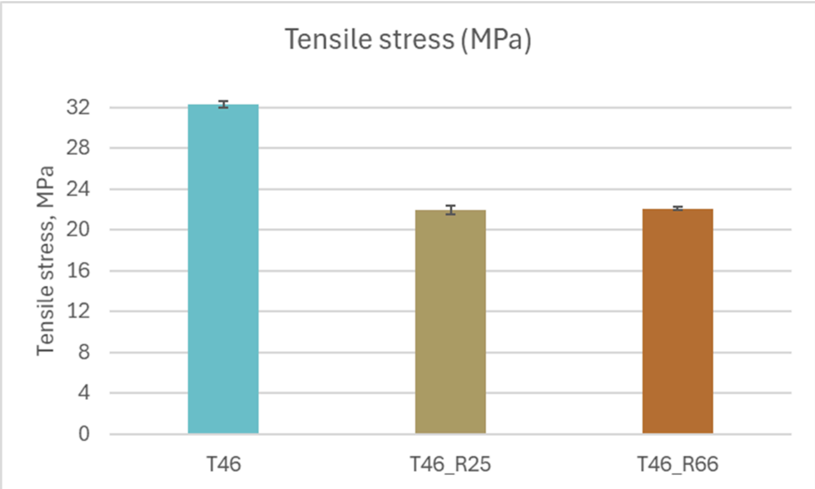

Figure 1: Tensile stress at break for three Turcon® T46 compounds: T46, T46_R25, and T46_R66 (PTFE compound with 66 wt.% bronze-filled PTFE repro in virgin PTFE).

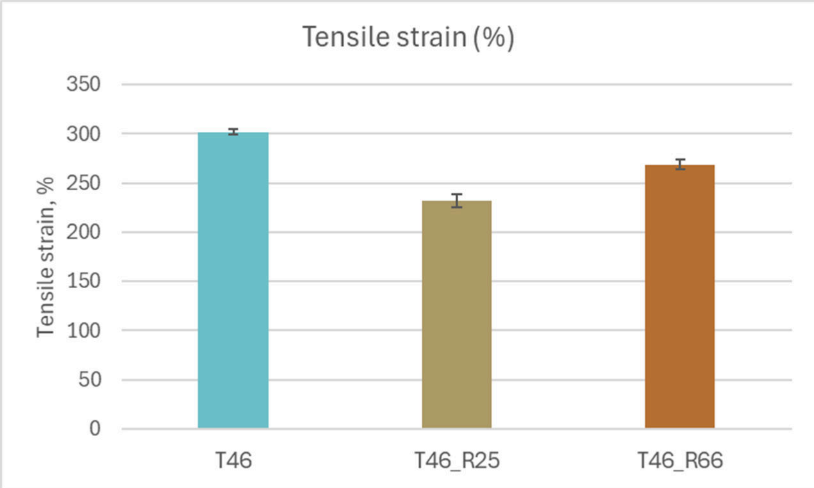

Figure 2: Tensile strain at break for three Turcon® T46 compounds: T46, T46_R25, and T46_R66 (PTFE compound with 66 wt.% bronze-filled PTFE repro and virgin PTFE).

Figures 1 and 2 show that the virgin T46 compound has the highest tensile stress, at 32.3 MPa, and the highest tensile strain at break, at 302%. Incorporating 25 wt.% repro into the T46 matrix leads to a pronounced reduction in tensile stress and tensile strain. At a 25 wt.% repro load in the T46 matrix, the tensile strength decreases to 21.9 MPa, a reduction of approximately 32% relative to virgin T46, while the tensile strain drops to 232%, indicating increased brittleness of the material. These results indicate poor accommodation and interfacial bonding of the repro particles in the T46 compound, which already contains a substantial fraction of bronze filler. The existing filler network limits the availability of the PTFE matrix to accommodate and bind additional particles, causing the repro to behave as poorly bonded inclusions that act as stress concentrators.

Interestingly, incorporating a higher content, 66 wt.%, into the virgin PTFE matrix did not result in further significant strength reduction compared with T46_R25. T46_R66 shows a visibly higher elongation of 269%, approaching the elongation of the virgin T46. The results suggest that a higher repro content can be incorporated into a virgin PTFE matrix than into a bronze-filled T46 matrix without compromising mechanical performance. This counterintuitive behavior suggests that, at high repro loadings, the repro becomes structurally integrated within the virgin PTFE matrix rather than acting as poorly bonded inclusions.

These findings demonstrate that mechanical performance does not scale linearly with repro content but instead depends strongly on the role of the repro particles within the compound architecture.

3.2 Influence of mineral-filled PTFE repro content and proprietary in- house re-pro preprocessing on the mechanical properties of the repro compounds

In contrast to the bronze-filled PTFE system, M12 is mineral fiber-filled PTFE system that showed a different response to repro incorporation.

Figure 3 shows the tensile stress at break as a function of repro content for the virgin M12 compound (used as a reference) and the M12 repro compounds with different repro loadings and with a repro particle size in the range of 100 to 150 µm. Figure 4 shows the tensile strain at break as a function of repro content for the virgin M12 compound (used as a reference) and the M12 compounds containing repro particles with a particle size in the range of 100 to 150 µm.

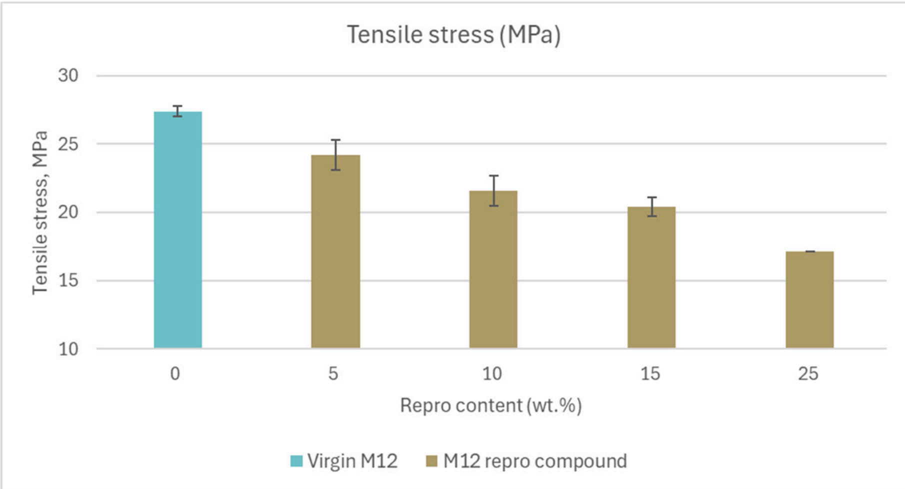

Figure 3: Tensile stress as a function of repro content for the virgin M12 compound (used as a reference) and M12 compounds containing repro particles with a repro particle size in the range of 100 to 150 µm.

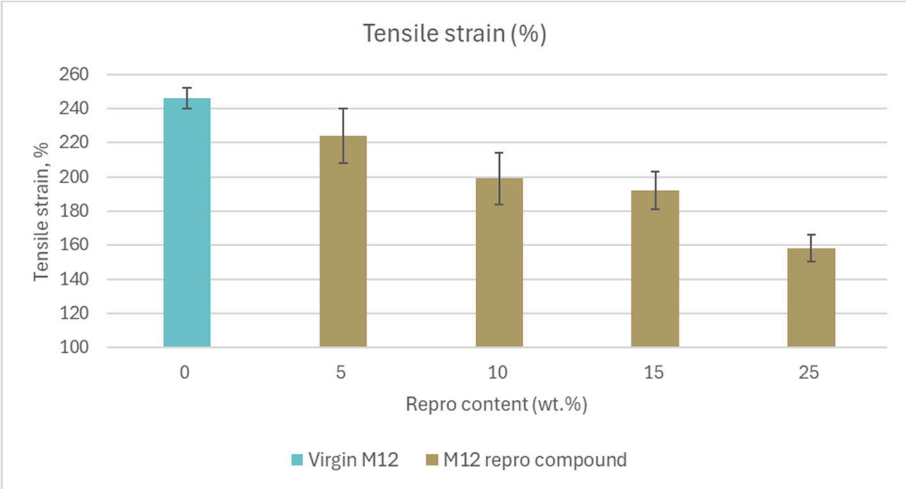

Figure 4: Tensile strain as a function of repro content for the virgin M12 compound (used as a reference) and M12 compounds containing repro particles with a repro particle size in the range of 100 to 150 µm.

Figures 3 and 4 show a continuous decrease in both tensile stress and tensile strain as the repro content increases. Even at the lowest investigated repro content of 5 wt.%, a pronounced reduction in tensile stress is observed, decreasing from 27.4 MPa for the virgin M12 compound to 24.2 MPa, with the tensile strain decreasing from 246% for the virgin M12 compound to 224%. With the further addition of repro, both tensile stress and tensile strain continue to drop, reaching 17.1 MPa and 158% at the highest investigated repro content of 25 wt.%. This corresponds to a decrease of approximately 38% in stress and 36% in elongation relative to the virgin M12 compound. The large repro particles (100-150 µm), combined with the presence of the rigid mineral fibers, amplify stress concentration effects and promotes interfacial debonding. This induces a pronounced decrease in tensile strength and a loss of ductility as the repro content increases, indicating a strong sensitivity of the material to the introduced defects.

To mitigate these negative effects and improve interfacial bonding between the M12 repro particles and the M12 virgin compound, a proprietary in-house handling of M12 repro was performed after the air classification processing step.

Figures 5 and 6 present the tensile stress and tensile strain, respectively, for the M12, M12_R15 and M12_PR15 compounds.

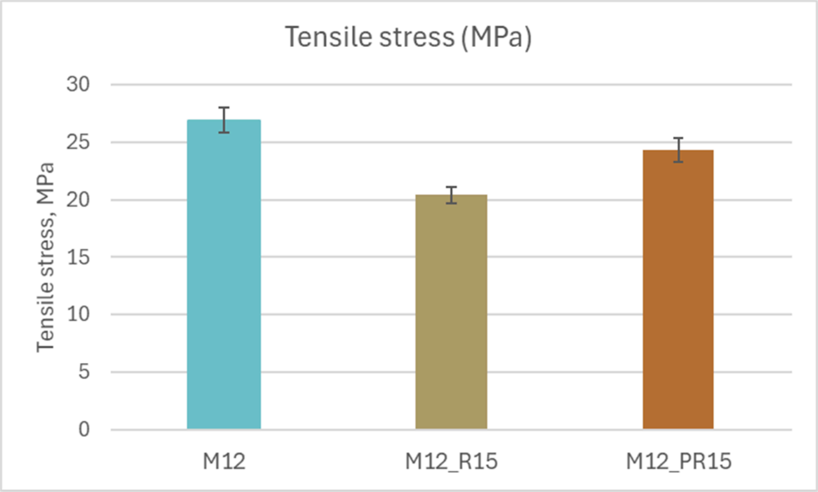

Figure 5: Tensile stress at break for three compounds: M12, M12_R15 and M12_PR15.

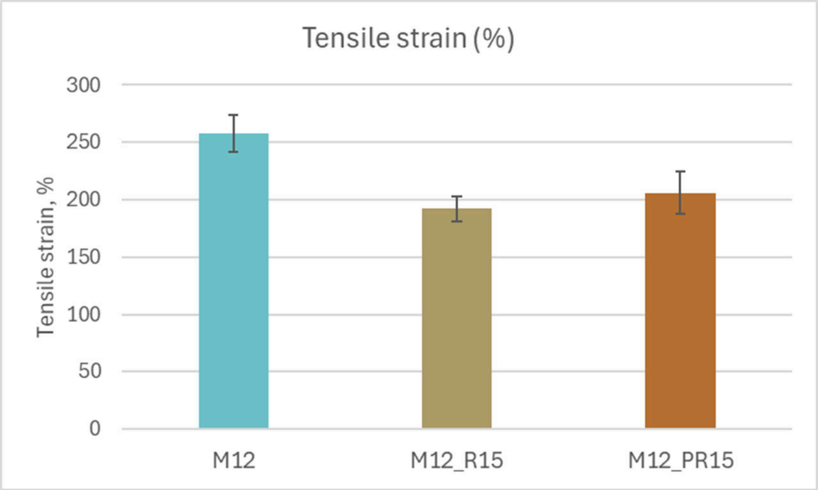

Figure 6: Tensile strain at break for three compounds: M12, M12_R15 and M12_PR15.

Figures 5 and 6 show that incorporating 15 wt.% of repro that was not subjected to proprietary processing results in a pronounced reduction in tensile stress, from 26.9 MPa to 20.4 MPa, and reduction in tensile strain, from 258 % to 192%.

When the M12 repro material is subjected to a special processing step after the classification process and prior to compounding, tensile strength improves significantly, reaching 24.3 MPa, while the tensile strain improves slightly, reaching 206%. Adding 15 wt.% of preprocessed M12 repro leads to a recovery of approximately 67% of the strength loss caused by adding untreated M12 repro, bringing the tensile strength close to that of the virgin M12 compound. Even though the tensile strain of

M12_PR15 remains below that of the virgin M12 compound, the preprocessing step recovers approximately 27% of strain loss caused by adding untreated M12 repro.

The data indicates that proprietary in-house processing of the repro material prior to compounding improves the interfacial bonding between the repro particles and the M12 virgin compound, thereby improving stress transfer and recovering the ductility of the M12 repro compound, which is highly sensitive to defects. Although the performance does not reach that of virgin M12, the results demonstrate that improved interfacial bonding can change the material response from defect-dominated toward more integrated behavior.

3.3 Sealing performance of the repro compounds

To validate the relevance of the mechanical observations under realistic operating conditions, selected compounds were subjected to dynamic seal tests. The results provide insight into how interactions between the repro and the material matrix translate into the tribological performance of the repro compounds.

3.3.1 T46-based compounds

Figure 7 presents friction force as a function of the number of cycles in the performance tests for three T46 compounds: T46, T46_R25, and T46_R66 (PTFE compound with 66 wt.% bronze-filled PTFE repro and virgin PTFE).

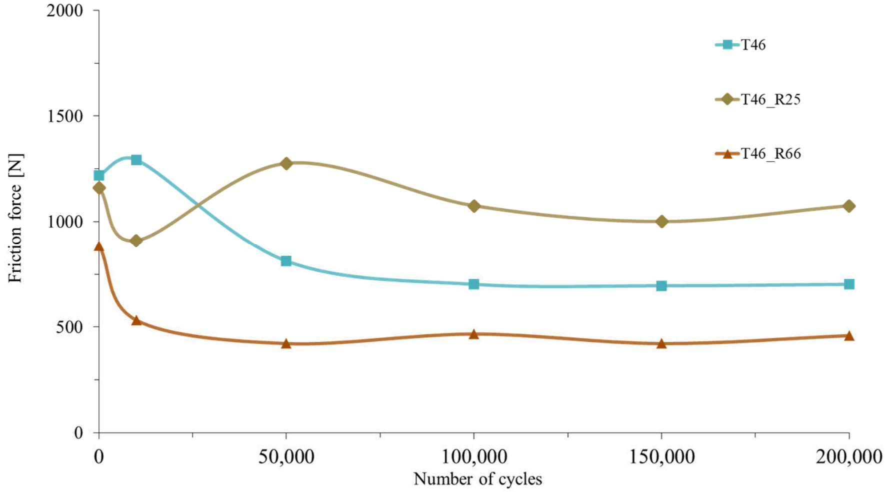

Figure 7: Friction force as a function of the number of cycles for three T46 compounds: T46, T46_R25, and T46_R66 (PTFE compound with 66 wt.% bronze-filled PTFE repro and virgin PTFE).

Figure 7 shows that the T46 compound initially has high friction, which gradually decreases after 10,000 cycles and stabilizes after approximately 50,000 cycles. T46_R25 shows a higher friction force and more friction fluctuation up to approximately 100,000 cycles, after which it becomes more stable. In contrast, T46_R66 shows the lowest and most stable friction force over the entire test range of 200,000 cycles, with a prominent drop in friction up to 10,000 cycles. These results align well with the mechanical observations. In the T46_R25 compound, the repro particles behave as poorly bonded inclusions rather than being fully incorporated in the matrix, leading to increased friction. In contrast, in T46_R66, the repro is effectively integrated in the virgin PTFE matrix, resulting in a more homogeneous material and more stable friction behavior.

The final leakage for all three tested compounds was negligible and close to zero, indicating that the differences in friction are not related to and do not cause a loss of the sealing function of the tested compounds.

The summarized wear and deformation measured after the seal tests for T46, T46_R25 and T46_R66 are presented in Figure 8.

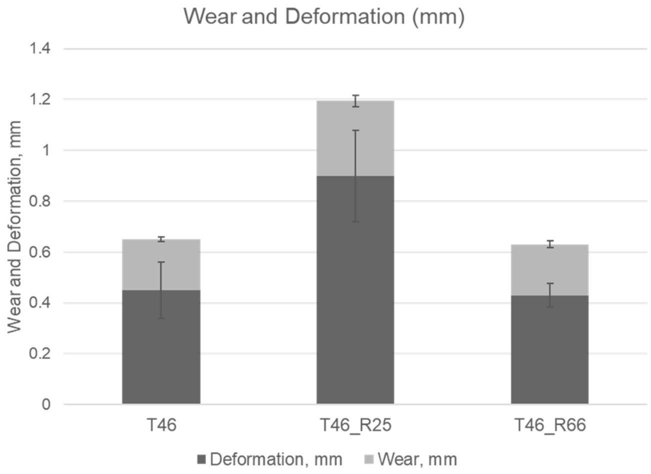

Figure 8: Wear and deformation for three T46 compounds: T46, T46_R25, and T46_R66 (PTFE compound with 66 wt.% bronze-filled PTFE repro and virgin PTFE).

Figure 8 shows that T46_R25 has the highest deformation, at 0.9 mm, and wear at 0.29 mm, indicating reduced resistance of the material to mechanical loading. In contrast, T46_R66 shows a deformation of 0.43 mm and wear of 0.2 mm, comparable to or slightly lower than the deformation and wear of virgin T46.

Representative seal cross-sections after testing, made from the virgin T46 compound, T46_R25 and T46_R66 are shown in Figure 9.

Figure 9: Seal cross-sections of three seals made of a) virgin T46, b) T46_R25, and c) T46_R66 (PTFE compound with 66 wt.% bronze-filled PTFE repro and virgin PTFE).

Differences in seal geometry and material integrity can be observed in Figure 9. These visual differences are consistent with the measured values of wear and deformation. The observed differences in color and contrast between the seal cross-section images are due to variations in microscope settings during image acquisition.

In summary, the seal test results for friction, wear and deformation for the three T46 compounds demonstrate that repro content alone is not the most dominant factor for seal performance. While 25 wt.% repro leads to increased friction, deformation and wear, a 66 wt.% repro content in a virgin PTFE matrix yields superior tribological and mechanical stability. These results indicate that a high repro content in virgin PTFE material does not inherently compromise seal performance. Instead, when the repro particles act as structural extensions of the material matrix, excellent seal performance can be achieved.

3.3.2 **M12-based compounds**

Figure 10 presents friction force as a function of the number of cycles in the performance tests for three M12 compounds: virgin M12, M12_R15 and M12_PR15.

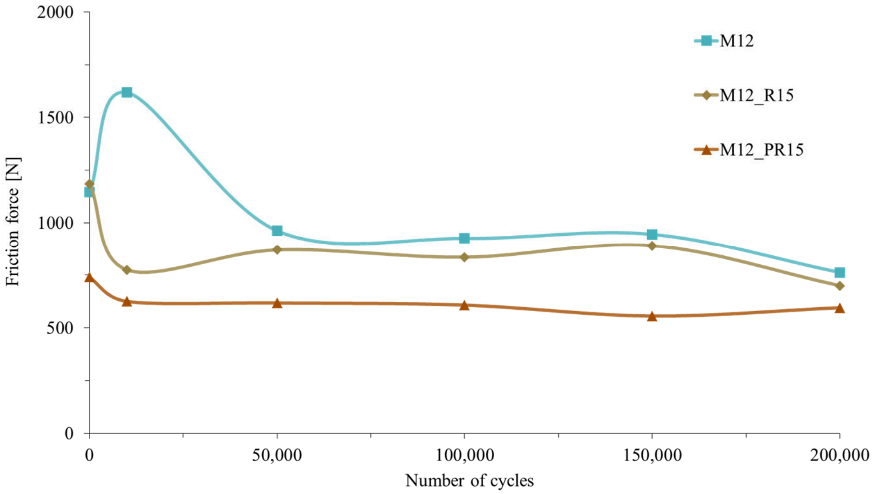

Figure 10: Friction force as a function of the number of cycles for three M12 compounds: virgin M12, M12_R15 and M12_PR15.

Figure 10 shows that the virgin M12 compound displays relatively high friction, with a pronounced peak in the early cycles. M12_R15 shows lower friction than virgin M12, with a noticeable drop in friction up to 10,000 cycles. In contrast, M12_PR15 shows the lowest friction over the entire test duration, with a slight drop in friction up to 10,000 cycles, after which it remains stable and almost without fluctuations. This indicates a significant improvement in tribological behavior due to improved interfacial bonding.

The leakage at the end of the test for all three tested compounds was negligible and close to zero, implying that the differences in friction did not induce failure in the sealing performance.

Wear and deformation are also measured after seal testing for virgin M12, M12_R15 and M12_PR15 and the results are presented in Figure 11.

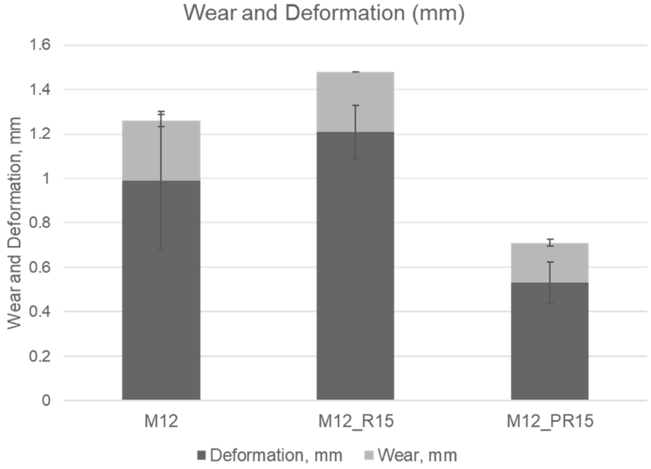

Figure 11: Wear and deformation of three M12 compounds: virgin M12, M12_R15, and M12_PR15.

M12_R15 shows the highest deformation, at 1.21 mm, indicating reduced resistance to mechanical loading compared with virgin M12. M12_PR15, on the other hand, shows a significant reduction in deformation, approximately 46% lower than that of virgin M12. Wear shows a similar trend to deformation. While virgin M12 and M12_R15 exhibit comparable wear levels of approximately 0.27 mm, M12_PR15 shows significantly lower wear, at 0.18 mm. These results suggest that the improvement in dimensional stability, as well as the improved resistance to mechanical load, are obtained through proprietary repro processing.

Figure 12 presents representative seal cross-sections after testing, made from virgin M12, M12_R15 and M12_PR15. These visual differences in seal geometry and material integrity are consistent with the measured values of wear and deformation. The color and contrast variations between the seal cross-section images arise from different microscope settings and are not related to differences in the materials.

Figure 12: Seal cross-sections of the three seals made of a) virgin M12, b) M12_R15, and c) M12_PR15.

Unlike T46, friction, wear and deformation results for the three M12 compounds demonstrate that the M12 compound is highly sensitive to the addition of repro unless the interfacial bonding is improved. The M12_PR15 compound exhibited better sealing performance compared to the virgin M12, despite slightly lower tensile strength and elongation values. The proprietary in-house processing of repro led to reduced friction, improved dimensional stability and lower wear. These results demonstrate that improved interfacial bonding can improve functional sealing behavior even when bulk mechanical properties are not fully recovered.

4 Summary and conclusion

This work demonstrates the incorporation of two different PTFE-based reproes, a bronze-filled PTFE repro and a mineral fiber-filled PTFE repro, in virgin PTFE compounds. The aim was to understand how repro content influences mechanical and sealing performance. Mechanical testing was used as an initial screening tool to evaluate the impact of repro addition on mechanical properties. For the Turcon® T46 system, mechanical results indicated that repro could be incorporated with limited loss of tensile strength and ductility, enabling the evaluation of both moderate and high repro contents in the seal test. T46_R66 exhibited low friction, limited wear and deformation and negligible leakage in the dynamic seal test, surpassing the performance of the virgin Turcon® T46. This behavior indicates that under stable conditions, repro particles can act as a structural continuation of the matrix enabling efficient stress transfer and stable seal performance. On the other hand, the T46_R25 showed increased friction and deformation, indicating that repro particles in a filler saturated matrix may act as poorly integrated inclusions. In contrast to bronze-filled PTFE repro compounds, the mineral fiber filled PTFE compound, Turcon® M12, exhibited strong sensitivity to repro addition. The addition of repro led to a significant reduction in mechanical properties and degraded seal performance. This behavior indicates that repro particles behave as defects, promoting stress concentration and crack initiation. However, subjecting repro to a proprietary preprocessing step slightly improved mechanical properties and significantly improved the tribological performance of the repro compound. The M12_PR15 showed superior sealing performance compared to the virgin compound, despite lower mechanical properties. This demonstrates that optimized interfacial bonding may be more critical than bulk strength for dynamic seal performance.

Results highlight that feasibility and repro incorporation strongly depend not on reducing the repro content, but on repro particle size, interfacial bonding and compound architecture (virgin PTFE or filled PTFE material). This work demonstrates that when repro is well integrated in the matrix material, circularity in the PTFE-based sealing materials is achievable without compromising seal performance. This demonstrates a technically validated route to integrating recycled content into PTFE-based sealing materials without compromising seal performance – a concrete step toward more circular sealing solutions.

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