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Surface roughness evolution of EPDM and its impact on the long-term sealant performance of gasketed joints of segmental shield tunnels

Évolution de la rugosité de surface de l'EPDM et son impact sur la performance à long terme des joints d'étanchéité des tunnels à bouclier segmentaire

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ABSTRACT: EPDM (Ethylene Propylene Diene Monomer) rubber gaskets were widely used as the waterproofing component at the joints of shield tunnels that are expected to serve for decades. However, the alterations in surface roughness of EPDM rubber gaskets due to ageing introduce an aspect that is not yet comprehensively understood in terms of its implications for sealant performance. In this study, a series of AFM (Atomic Force Microscope) tests were conducted on 6 groups of squared EPDM thin slices, each of which had been oxidatively aged to different levels before the tests. The analysis encompassed the determination of both the fractal dimension and the RMS (Root Mean Square)-slope of the surfaces. Supplementary tests utilizing Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) were performed to elucidate the mechanisms governing surface roughening. The results show that the mean value of fractal dimension of EPDM specimens first decreased to 2.16 after 11.2-hour ageing and then increased to 2.42 after 39h-ageing. The evolution of RMS-slope exhibited similar tendencies, escalating from 0.55 to 1.16. Finally, a theoretical model to prognosticate the long-term waterproof capacity based on the percolation theory was proposed, which explicitly incorporated the impact of surface roughness. The outcomes underscore the considerable hydraulic deterioration resulting from surface roughening over a prolonged duration, ultimately leading to the complete loss of waterproof capacity in large opening scenarios.

RÉSUMÉ: Les joints en caoutchouc EPDM ont été largement utilisés comme composants d'étanchéité au niveau des joints des tunnels de protection qui sont censés fonctionner pendant des décennies. Toutefois, les modifications de la rugosité de la surface des joints en caoutchouc EPDM dues au vieillissement constituent un aspect qui n'est pas encore bien compris en termes d'implications pour les performances du mastic d'étanchéité. Dans cette étude, une série de tests AFM a été menée sur 6 groupes de tranches minces d'EPDM carrées, chacune ayant été vieillie par oxydation à différents niveaux avant les tests. L'analyse a porté sur la détermination de la dimension fractale et de la RMS-slope des surfaces. Des tests supplémentaires utilisant la SEM et la FTIR ont été réalisés pour élucider les mécanismes régissant la rugosité de la surface. Les résultats montrent que la valeur moyenne de la dimension fractale des échantillons d'EPDM a d'abord diminué à 2,16 après un vieillissement de 11,2 heures, puis a augmenté à 2,42 après un vieillissement de 39 heures. L'évolution de la pente RMS a montré des tendances similaires, passant de 0,55 à 1,16. Enfin, un modèle théorique a été proposé pour pronostiquer la capacité d'imperméabilisation à long terme sur la base de la théorie de la percolation, qui intègre explicitement l'impact de la rugosité de la surface. Les résultats soulignent la détérioration hydraulique considérable résultant de la rugosité de la surface sur une période prolongée, conduisant finalement à la perte totale de la capacité d'étanchéité dans les scénarios de grande ouverture.

Keywords: Shield tunnel; gasketed joint; sealant performance; EPDM; surface roughness.

1 INTRODUCTION

The hydraulic deterioration of gasketed joints causes leakage defects in shield tunnels in the long term (Xie et al., 2023b). Figure 1 depicts the progressive deterioration of the leakage defects, initially manifesting as wet stains, subsequently evolving into joint leakage indicative of substantial groundwater infiltration, and ultimately culminating in the water and soil gushing, signifying that the gasketed joints have lost all waterproof capacity. Hence, it is of great importance to elucidate the long-term sealant performance of gasketed joints (Shi et al., 2015).

Investigators have highlighted that the sealant performance of gasketed joints is a typical hydro-mechanical behaviour, prominently influenced by the assembly conditions of joints, i.e., the opening, offset, and rotation (Gong et al., 2018). Another main factor is the time-dependent behaviour of EPDM material, with stress relaxation constituting the predominant focus in prior investigations (Arnau et al., 2012; Shi et al., 2015; Zhang et al., 2020).

Figure 1. Leakage defects in shield tunnels.

However, the surface roughening of rubber surfaces, constituting another pivotal time-dependent attribute, has often been overlooked in analysing the sealant performance of gasketed joints. Physicians have underscored that the surface roughness has a significant effect on the sealant and seepage behaviours of the rubber seals (Persson, 2022; Persson and Yang, 2008). With an increase in surface roughness, the likelihood of leakage occurring at lower water pressures amplifies. Concurrently, the hydraulic aperture widens, consequently augmenting hydraulic conductivity. Thus, neglecting the phenomenon of surface roughening in gasketed joints may lead to an overestimation of waterproof capacity especially, in the long term.

In this paper, a comprehensive characterisation of the surface roughening phenomenon in EPDM was carried out through the utilisation of AFM tests. Additionally, SEM and FTIR tests were performed to elucidate the underlying mechanisms induced by the ageing process. Then, a refined theoretical model based on percolation theory was proposed to capture the influence of surface roughening on sealant performance. Finally, the model was applied in a specific engineering case, with its long-term waterproof capacity presented.

2 FRACTAL CHARACTERISTICS OF EPDM MATERIAL

2.1 Test methods

In the test, 6 groups of EPDM samples (see Figure 2(a)) were prepared, with dimensions measuring 6 mm × 6 mm × 2 mm. To enhance the generality of our findings, each set underwent three parallel tests. These groups were subsequently subjected to the thermo-oxidative ageing at a temperature of 150 °C for varying duration: 0 (unaged), 6.7, 11.2, 16.7, 22.3 and 39 h, as delineated in Figure 2(b) and tabulated in Table 1. Note that the upper side of the EPDM sample was scanned in the AFM test, as depicted in Figure 2(c). This approach ensured that the testing surface was in full contact with oxygen throughout the ageing process.

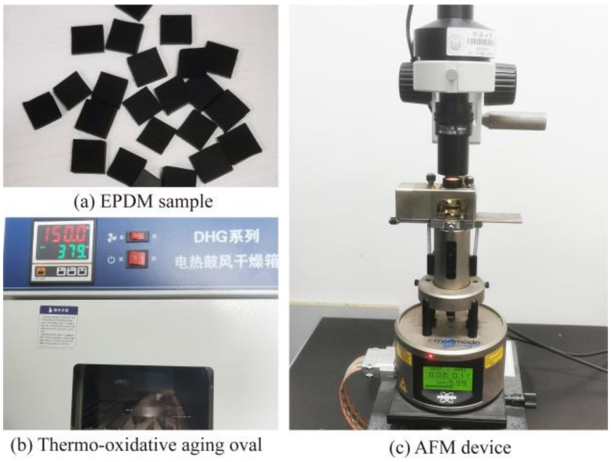

Figure 2. EPDM samples and test devices.

2.2 AFM results

Figure 3 depicts the surface topography of 6 groups, employing an observation scale of 5 μm × 5 μm. The outcomes indicate that the unaged EPDM surface (A1) exhibits a distinct degree of roughness, marked by the dense presence of clustered particles, as illustrated in Figure 3 (a). In the early stage of ageing process as shown in Figure 3 (b) and (c), the EPDM surfaces barely change in surface morphology, and with slightly smoother appearance compared with the unaged scenario in A3.

In the subsequent ageing periods, spanning from A4 to A6, a greater number of particles are observed to detach and accumulate on the EPDM surface over time, leading to the development of pronounced spikes. Importantly, these spikes formed through ageing are notably sharper in comparison to those on the original surface, signifying a progressive increase in surface roughness. This qualitative evolution, as indicated by the test outcomes, is similar to that from Wang et al. (2020), suggesting that while the waterproof capacity might experience an initial enhancement within a short timeframe, it subsequently diminishes over prolonged duration, in alignment with the progression of roughness.

Table 1. Ageing times for each group.

group	A1	A2	A3	A4	A5	A6
Ageing time (h)	0	6.7	11.2	16.7	22.3	39

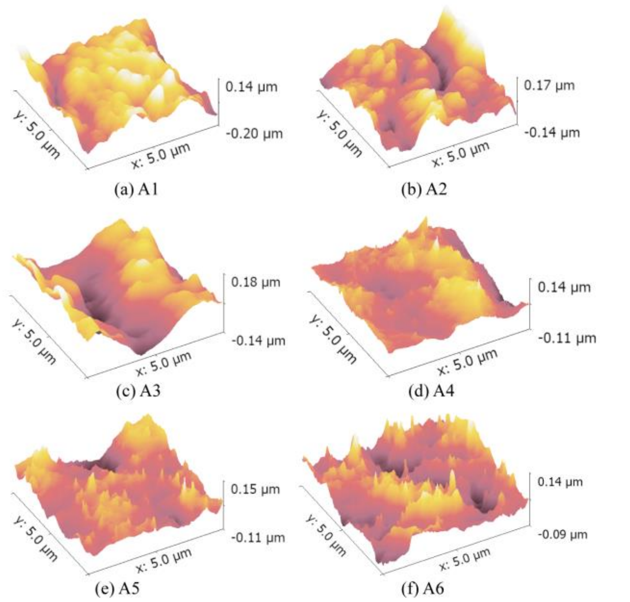

Figure 3. Surface roughness of different groups.

Figure 4 presents the evolution of fractal dimension D_f of the EPDM surface based on the obtained test data using the method of enclosing boxes. The D_f results in the same group exhibit certain disparities, attributed to the inherent discreteness of the surface topography. Nevertheless, the nonlinear variation of D_f with ageing time underscores the shift towards smoother surfaces initially, followed by a transition to increased roughness once the ageing duration surpasses 11.2 hours, corroborating observations in Figure 3. Specifically, the mean value of D_f firstly decreased from 2.27 to 2.16 after 11.2-hour ageing, subsequently ascending to 2.42 following 39-hour ageing.

RMS-slope ξ, another roughness-related parameter, can also be derived from the test data. Figure 5 presents the parallel results of RMS-slope, mirroring a comparable nonlinear ascending pattern as observed in the fractal dimension. Specifically, ξ experiences a slight reduction until the ageing duration reaches 11.2 h, after which it undergoes a significant escalation. When the ageing time approaches 39 h, the average value of ξ culminates at 1.16, notably surpassing that of 0.55 in the unaged scenario.

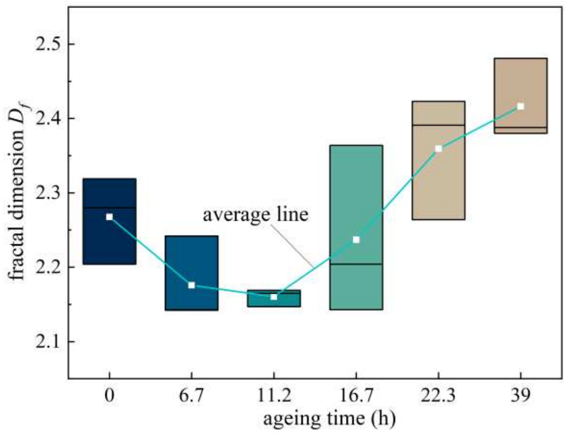

Figure 4. Fractal dimension of EPDM surface.

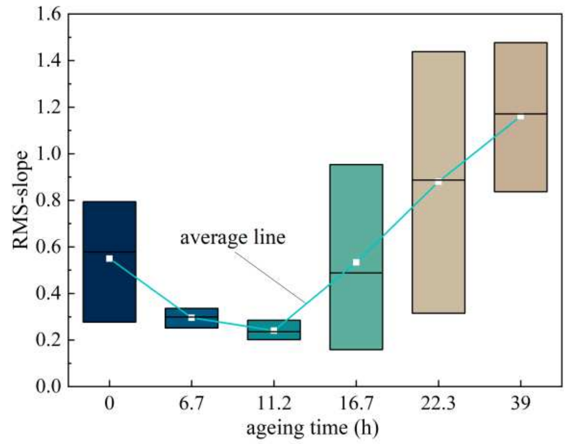

Figure 5. RMS-slope of EPDM surface.

2.3 SEM and FTIR results

To reveal the ageing mechanisms of EPDM surface, a series of SEM and FTIR tests were conducted. Figure 6 gives the surface roughness evolution over time observed through SEM scans, primarily capturing the degradation process prompted by elevated temperature. Evidently, an increased presence of particles becomes apparent, with a dense distribution observed on the EPDM surface. This observation aligns with the findings obtained from the AFM analysis, as illustrated in Figure 3.

Figure 7 graphically illustrates the alterations in chemical composition throughout the degradation process, revealing that ageing predominantly impacts components characterized by wave numbers proximate to 1500 cm^{-1}. This specific wave number range corresponds to the scissoring vibration of C-H bonds, with the intensity of its peak serving as an indicator of material degradation. Notably, the peak intensity of the unaged sample is lower than that of the subsequent instances, offering insights into the chemical mechanisms driving the initial surface smoothing observed during the early stages of ageing in the AFM results.

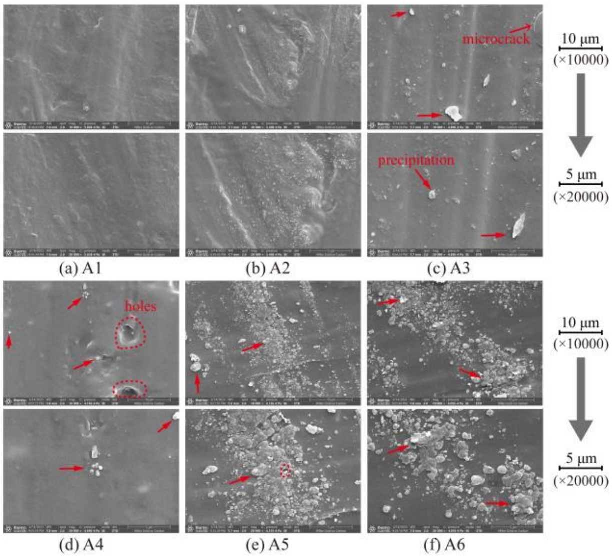

Figure 6. SEM results of EPDM surface of different ageing conditions from A1 to A6.

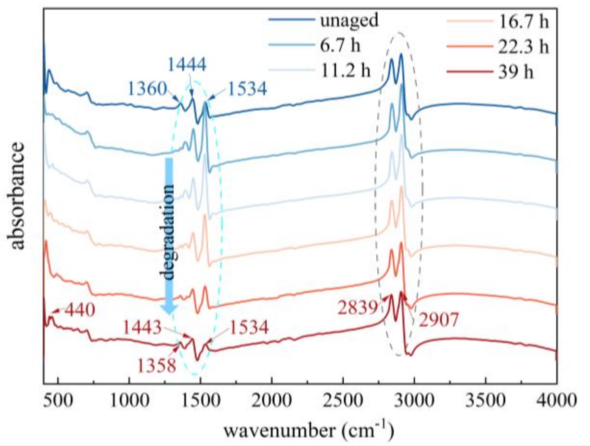

Figure 7. FTIR results of EPDM material of different ageing conditions from A1 to A6.

3 THEORETICAL MODEL OF SEALANT PERFORMANCE

Herein, a refined theoretical model aimed at assessing the sealant performance was introduced (Xie et al., 2023a). In the derivation, the percolation pressure (Persson, 2022) has been employed to elucidate the impact of surface roughness.

3.1 Percolation pressure

According to percolation theory, leakage from the contact area is prevented when the surface percolates at the highest magnification, i.e., the relative contact area $A(\zeta)/A_0$ exceeds 0.4 (Persson, 2022). Accordingly, we define the nominal pressure as percolation pressure P_{perc} when $A(\zeta)/A_0$ reaches 0.4 at a large wavenumber cut-off (Persson, 2022):

$$P_{perc} = \frac{\sqrt{2}}{2}\operatorname{erfinv}\left(\frac{A}{A_0}\right)E^*\xi \qquad (1)$$

where E^* refers to the effective modulus of the rubber seals, and equals to $E_g/\left(2\times\left(1-v_g^2\right)\right)$ when the seal is composed of two pieces of gaskets in shield tunnel. v_g is the equivalent Poisson ratio of the gaskets, which varies with the compression strain.

3.2 Theoretical model implemented with percolation theory

The sealant performance of the gasketed joints is primarily influenced by the normal confining pressure P_c (Gong et al., 2019). This normal confining pressure undergoes augmentation when subjected to water pressurisation, a phenomenon recognised as the self-sealing effect (Shalabi et al., 2016), characterised by the slope k_0. Notably, the self-sealing effect becomes increasingly prominent, ultimately leading to the establishment of a critical leakage state when the confining pressure P_{c2} attains a value equivalent to the critical leakage water pressure P_{wc}

$$P_{wc} = \frac{1}{1-k_0}P_{c1} \qquad (2)$$

where k_0 is the self-sealing coefficient and varies with compression strain ε, and P_{c1} refers to the initial confining pressure

$$P_{c1} = E_g\varepsilon \qquad (3)$$

According to the previously mentioned percolation theory, the leakage transpires prior to the onset of the critical leakage state. By incorporating the influence of the percolation process, as symbolised by the percolation pressure P_{perc}, the final equation governing the critical water pressure (Xie et al., 2023a) can be derived as

$$P_{wc} = \frac{E_g\varepsilon - P_{perc}}{1-k_0} \qquad (4)$$

Notably, Eq. (4) reflects the effect of surface roughness on waterproof capacity, that is, P_{wc} reduces as the EPDM surface gets rougher.

3.3 Model validation and long-term sealant performance prediction

Based on the proposed theoretical model, the long-term sealant performance of gasketed joints can be prognosticated. The test data from Gong et al. (2018) is used in the model validation. One representative engineering case, labelled as SC1, is subjected to analysis. First, the equivalent modulus of the gaskets E_g is derived based on the data of gasket-in-groove loading test, as given in Eq. (5):

$$E_g = 3 + 1.429 \times 10^{-6} \exp(36.81\varepsilon) \tag{5}$$

Significant nonlinearity of self-sealing effect is observed in these cases. Based on the test data (Gong et al., 2018), a correlation between the slope and compression strain (Xie et al., 2023a) was established. The results indicate that k_0 equal to $4.46\varepsilon^2$. The results of RMS-slope derived from the AFM test are used in calculating the percolation pressure. In the initial unaged condition, RMS-slope registers at 0.55, while following a 39-hour ageing period (full aged), this value increases to 1.16.

Figure 8 present the experimental and theoretical results of critical leakage pressure for case SC1. The results show that the theoretical results in unaged scenario align closely with the test data. When the opening is small, the theoretical estimations slightly exceed the experimental values. This discrepancy suggests an underestimation of the confining pressure within the theoretical model. One main reason for this is that the equivalent modulus is determined through the gasket-in-groove loading test, which does not account for lateral water pressurization. The modulus E_g is further enhanced under enormous water pressure.

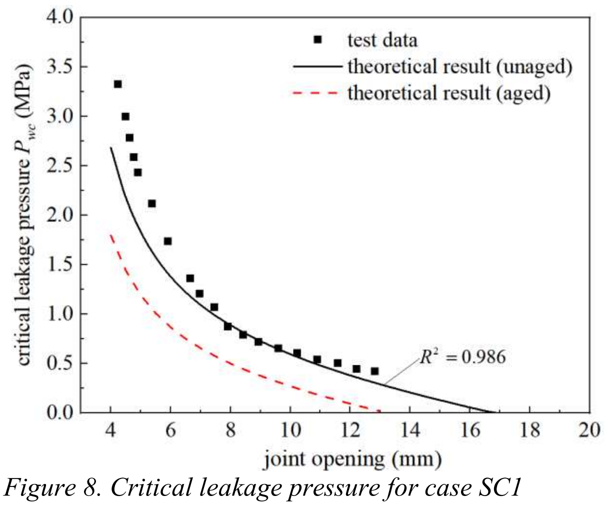

Figure 8. Critical leakage pressure for case SC1

The results of aged scenario represented in dashed lines indicate that the surface roughening has great effect of hydraulic deterioration. The critical leakage pressure experiences substantial decreases across all opening situations, causing the critical leakage pressure P_{wc} approaches 0 much earlier compared to the unaged scenario. The complete loss of waterproofing capacity occurs when the joint opening increases to 13 mm, primarily due to the escalating percolation pressure. In the unaged scenario, this critical opening value is approximately 17 mm.

According to the Arrhenius formula (Zhang et al., 2020), 39-h ageing time at 150°C corresponds to an 80-year service duration at room temperature (20°C). These findings underscore the substantial contribution of ageing-induced surface roughening in EPDM to the long-term hydraulic deterioration of gasketed joints.

4 CONCLUSIONS

The paper mainly focuses on the roughness evolution of EPDM surface induced by ageing, and its long-term implications on the sealant performance of gasketed joints. The results of AFM test reveal a distinctive pattern: the EPDM surface initially experiences a slightly smoothing effect during the early stages of ageing, followed by a progressive increase in roughness after approximately 39-hour ageing. This evolutionary trajectory is further corroborated by the outcomes derived from SEM and FTIR tests.

In response to these findings, a refined theoretical model is introduced to evaluate the long-term sealant performance of gasketed joints. The results underscore the substantial effect of surface roughening on the hydraulic deterioration. Specifically, the gasketed joints lose all waterproof capacity when opening is 17 and 13 mm, in the unaged and aged scenarios, respectively. These findings serve to underscore the critical significance of incorporating the concept of surface roughening in the evaluation of sealant performance of gasketed joints, which also aids in the design of waterproof in segmental tunnels by predicting the waterproof capacity affected by surface roughness and joint deformations.

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REFERENCES

Arnau, O., Molins, C., Blom, C. B. M. and Walraven, J. C. (2012) Longitudinal time-dependent response of segmental tunnel linings, *Tunnelling and Underground Space Technology*, 28(1), pp. 98-108, https://doi.org/10.1016/j.tust.2011.10.002.

Gong, C., Ding, W., Soga, K. and Mosalam, K. M. (2019) Failure mechanism of joint waterproofing in precast segmental tunnel linings, *Tunnelling and Underground Space Technology*, 84, pp. 334-352, https://doi.org/10.1016/j.tust.2018.11.003.

Gong, C., Ding, W., Soga, K., Mosalam, K. M. and Tuo, Y. F. (2018) Sealant behavior of gasketed segmental joints in shield tunnels: An experimental and numerical study, *Tunnelling and Underground Space Technology*, 77, pp. 127-141, https://doi.org/10.1016/j.tust.2018.03.029.

Persson, B. N. J. (2022) Fluid Leakage in Static Rubber Seals, *Tribology Letters*, 70(2), pp. 1-10, https://doi.org/10.1007/s11249-022-01573-8.

Persson, B. N. J. and Yang, C. (2008) Theory of the leak-rate of seals, *Journal of Physics Condensed Matter*, 20(31), pp. 1-11, https://doi.org/10.1088/0953-8984/20/31/315011.

Shalabi, F. I., Cording, E. J. and Paul, S. L. (2016) Sealant behavior of gasketed segmental tunnel lining – Conceptual model, *Geomechanik Und Tunnelbau*, 9(4), pp. 345-355, https://doi.org/10.1002/geot.201500030.

Shi, C., Cao, C., Lei, M., Peng, L. and Shen, J. (2015) Time-dependent performance and constitutive model of EPDM rubber gasket used for tunnel segment joints, *Tunnelling and Underground Space Technology*, 50, pp. 490-498, https://doi.org/10.1016/j.tust.2015.09.004.

Wang, Y., Yang, Y., Su, F. and Wang, L. (2020) Multiscale analytical method and its parametric study for lining joint leakage of shield tunnel, *Applied Sciences (Switzerland)*, 10(23), pp. 1-21, https://doi.org/10.3390/app10238528.

Xie, J., Huang, X. and Jin, G. (2023a) Analytical model for the sealant performance of tunnel gasketed joints based on multi-scale contact and percolation theories, *Underground Space*, 14, pp. 319-337, https://doi.org/10.1016/j.undsp.2023.08.004.

Xie, J., Huang, X., Zhang, Z. and Jin, G. (2023b) Cohesive zone model-based analyses of localized leakage of segmentally lined tunnels, *Frontiers of Structural and Civil Engineering*, 17, pp. 503-521, https://doi.org/10.1007/s11709-023-0927-4.

Zhang, Z., Zhang, J., Huang, X. and Zhuang, Q. (2020) Experimental study on prediction of long-term durability of sealing gasket of shield tunnel. *Journal of Zhejiang University (Engineering Science)*, 54(1), pp. 118-125, https://doi.org/10.3785/j.issn.1008-973X.2020.01.014.