Test procedure for the estimation of the service life of PVC-P-based geosynthetic barriers (GBR-P) in road tunnel sealing systems

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ABSTRACT: This paper deals with the determination of test criteria for the durability assessment of PVC-based GBR-P products in tunnel sealing systems. In a completed research study different products for road tunnel application were investigated by systematic long time storage in hot water using an accelerated test procedure based on SIA V 280 standard (test no. 13) and EN 14415 (leaching test). The objective of this research study was to derive suitable exposure conditions and criteria for a practical test procedure with regard to service lifetimes of more than 100 years. To achieve this, test temperature and time as well as the best suitable test medium were investigated in a structured way. To compare the results of the new test procedure the material properties of in situ aged GBR-P samples removed from older road tunnels were investigated. Finally the derived new test procedure including the obtained optimum test criteria was incorporated in the update of the German regulations for road tunnel sealing systems (TL/TP KDB) which will be published in 2017.

Keywords: durability, road tunnel sealing system, PVC-based geosynthetic barrier (GBR-P), service life

1 INTRODUCTION

Tunnels built using the mining construction method are generally sealed against mountain water by a sealing system (Fig. 1) with polymeric geosynthetic (fluid) barriers (GBR-P). The GBR-Ps in tunnel sealing systems must reliably fulfill their function during the whole service life of the tunnel structure of regularly 130 years (ABBV 2010). A simple replacement of the GBR-P or the installation of an equal alternative is normally not possible or only with considerable effort. Therefore a high quality of the GBR-P products installed in a road tunnel is very important for owners and operators of these infrastructures. The durability of the GBR-P products ensuring a service life of more than 100 years is - beside the correct and careful installation in the tunnel - one of the key aspects in order to ensure watertightness and by this a high operational reliability of the tunnel over the whole lifetime.

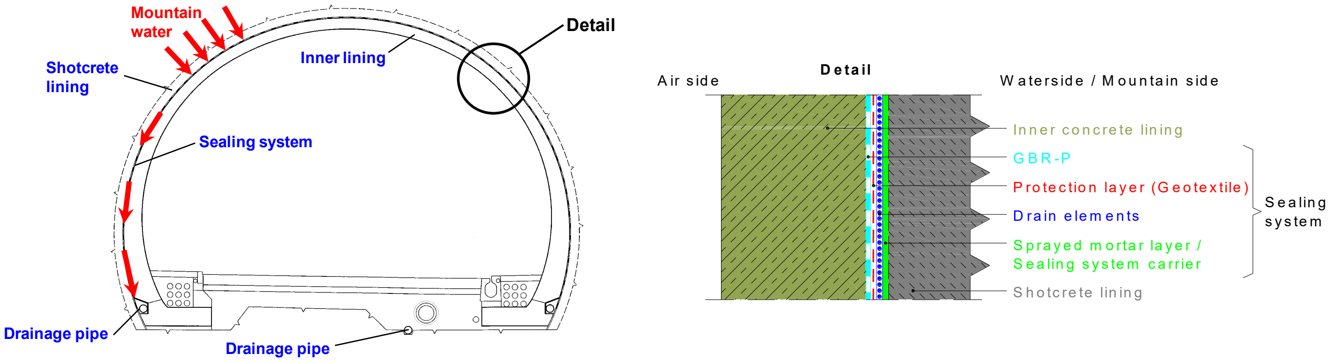

Figure 1. Road tunnel sealing system according to EAG-EDT (2005) and ZTV-ING (2007).

This paper presents the results of a Federal Highway Research Institute (BASt) research project which deals with the determination of test criteria for the durability assessment of PVC-based GBR-P products in tunnel sealing systems. In the project different products for road tunnel application were investigated by systematic long time storage in hot water using a new test procedure based on SIA V 280 standard (test no. 13) and DIN EN 14415. By this the migration of the plasticizer, which is the decisive ageing mechanism for PVC based GBR-P products (ISO/TS 13434), is accelerated tested with an innovative test setup. The objective of this research project was to derive suitable exposure conditions and criteria for a practical testing procedure with regard to service lifetimes of more than 100 years. For that test temperature and time as well as the best suitable test medium were investigated in a structured way. Existing published investigations with a similar test program are used to compare and verify the results (Kramer et al. 2014).

To verify the new test procedure the material properties of GBR-P samples removed from two older road tunnels were investigated. In order to assess the in situ exposure conditions of the aged GBR-P samples, mountain water samples as well as other parts of the sealing system (e.g. protection layer / geotextile) were investigated. The mechanical properties derived from the investigation of in situ aged samples from other tunnels were also used to verify the here presented results (Robertson et al. 2014, Beer et al. 2013 and Maehner & Lange 2008).

2 MATERIALS

2.1 *GBR-P products for immersion tests*

After surveying the current market of PVC-P based GBR-P products for tunnel sealing systems, two commercially available GBR-P products were selected and provided by two different manufacturers. These GBR-P products are based on PVC-P, and the nominal thickness of the geosynthetic barriers are 2 mm. The GBR-P products consist of two co-extruded polymer layers: The primary layer which is the main sealing element is black and the thin secondary liner (≤ 0.2 mm), the so-called signal layer, is brightly colored. The signal layer should help to detect defects in the geosynthetic barrier which could happen e.g. during installation of the reinforcement for the inner concrete lining of the tunnel (Fig. 1). Table 1 shows the initial material properties of the investigated new products prior to ageing. Basic information about the products such as type and amount of plasticizer was not disclosed by the manufacturers. However, chemical analyses of product 1indicate a plasticizer content of approximately 25% referring to the total product weight.

Table 1. Initial mechanical properties of the GBR-P products.

Product	Thickness / mm	Tensile properties (CMD)		
		Tensile strength at break / N/mm^2	Elongation at break / %	E-Modulus / N/mm^2
1	2,00±0,01	18,2±0,3	460±6	15,3±0,4
2	1,99±0,01	16,9±0,5	476±13	11,6±0,6

2.2 *In situ aged material samples*

For the validation of the test method described in section 3.4 material samples from two existing road tunnels were used. Based on the material properties of these 30 and 23 years in situ aged PVC-P based GBR-P products together with the exposure conditions in the tunnel (temperature, mountain water characteristics) statements about the ageing of GBR-P products in reality were derived and compared with the laboratory test results described in section 3.4. The extraction of GBR-P samples aged under real conditions was done at the two different tunnels during comprehensive structural retrofitting projects. In order to shorten emergency exit distances, which is a requirement of the European tunnel directive (EC 2004), the two tunnels are retrofitted with additional safety installations, among them parallel rescue tunnels with new cross passages to the existing tunnel tubes. Here the existing tunnel tube is opened and there is the unique opportunity to inspect the old sealing system and to gain material samples from the different cross passages for further investigation (Fig. 2). The extraction of material samples was done very carefully in order not to damage the samples. The mechanical material properties of the samples were investigated in the laboratory at BASt. In order to assess changes of the mechanical properties of the GBR-P samples due to ageing the initial product characteristics could be very useful. Unfortunately no information about initial product characteristics could be investigated for the two tunnels reported here due to the long time period since installation of the sealing system. There is no obligation for the manufacturer or the tunnel owner to store such information for time periods extending 10 years. According to the information available in the German road infrastructure database the same product had been used for both tunnels.

Parallel to the removal of the GBR-P samples the temperature and chemical composition of the mountain water was investigated on site and in the laboratory.

Figure 2. GBR-P samples taken from an old road tunnel at the location of a new cross passage (picture: left: ABD Südbayern, right: BASt).

3 TESTING PROGRAM AND METHODS

3.1 *Overview of the experimental investigations*

The systematic investigation of the GBR-P products and the mountain water samples includes the following testing methods:

- Characterization received prior to ageing and after the accelerated ageing procedure (immersion tests)
  - Tensile test (DIN EN ISO 527-1, 3)
  - Surface weight (DIN EN 14415)
  - Thickness (DIN EN 1849-2)
  - Plasticizer type and content determined by gas chromatography
- Immersion test based on SIA V 280 standard (test no. 13) and DIN EN 14415
  - Immersion test at 60°C, 80°C and 85°C with de-ionized water
  - Immersion test at 80°C in an aqueous medium with pH 10
  - Immersion test at 80°C with de-ionized water and with permanent active carbon treatment
- Characterization of in situ aged GBR-P samples
  - Tensile test (DIN EN ISO 527-1,2,3)
  - Surface weight (DIN EN 14415)
  - Thickness (DIN EN 1849-2)
- Characterization of mountain water samples
  - Temperature (in situ measurement with GREISINGER, GMH 5530 measuring device and sensor Pt1000, measuring range -5 - 150°C).
  - pH-value (in situ measurement with same device and sensor GE 100, measuring range pH 0-14, 0-80°C).
  - Oxygen content (in situ measurement with WTW, Oxi 3210 measuring device and dissolved oxygen sensor CellOx 325, measuring range 0-50 mg/l).
  - Conductivity (in situ measurement with WTW, Cond 3110 and sensor TetraCon 325, measuring range 1µS/cm - 2 S/cm).

3.2 *Tensile tests*

All tensile test measurements are performed with a Zwick/Roell tensile testing machine (Model BZ1-MM14450.ZW04). The tensile tests are performed in an air conditioned environment at 23±2°C and a relative humidity of 50±10% (ISO 291:2008). Tensile tests are performed on the test specimen of Type 5 (DIN EN ISO 527-3). For the tensile test measurements, a free clamping length of 80 mm and a test speed of 100 mm/min (according to TL/TP KDB 2007) are used. The elongation at break is measured via the traverse displacement of the test machine. The E-modulus is determined at 1% up to 2% of the initial elongation and with a speed of 5 mm/min. The type of E-modulus determination is the secant inclination. Approximately six samples of each exposure (three for cross-machine direction (CMD) and three for machine direction (MD)) are tested and the average value is reported. The changes in the mechanical properties in relation to the initial value are calculated according to DIN EN 12226 with following equation:

$$R_F = \frac{F_\varepsilon}{F_C} \cdot 100 \quad (1)$$

$$R_\varepsilon = \frac{\varepsilon_\varepsilon}{\varepsilon_c} \cdot 100 \quad (2)$$

R_F represents the change in tensile strength and R_ε the change in elongation. F_ε and ε_ε represents the average tensile strength and elongation at break at maximum load of the accelerated aged specimens, and F_C and ε_C of the initial value of the tensile properties obtained by the control specimen.

3.3 *Surface weight*

Prior to weighing of the GBR-P samples they are dried (24h) in an air circulating hot cupboard at a temperature of 50±0,8°C (DIN EN 14415). Afterwards the GBR-P samples are stored under vacuum in an exsiccator until the reference atmosphere is reached (DIN EN ISO 291). This procedure is repeated until the change in weight between the last two dryings is less than 0.2%. The scales used to determine the surface weight is a Sartorius CPA1003S with an accuracy of +/-0.001 g.

3.4 *Immersion tests*

3.4.1 *Test setup and equipment*

The test setup for the immersion tests is a completely new development and is based on the requirements defined in SIA V 280 standard (test no. 13) and DIN EN 14415. The immersion tests aim at accelerating the migration of the plasticizer, which is the decisive ageing mechanism for PVC-based GBR-P products. Figure 3 shows the test setup of the immersion tests. For the immersion tests stainless steel basins with 38 l volume are used. This volume allows for a mass ratio between test samples and test medium of minimum 1:40. The aqueous medium is heated and circulated by a Julabo heating immersion circulator allowing a test media flow rate of 2 l/min with a temperature constancy of 0.03 °C. Compensating reservoirs with automatic refill control are used in order to compensate the evaporation losses. The sample holders for the test specimens as well as the fixing devices are all made of stainless steel (Fig. 3). The test samples (plates 215 x 95 mm) are immersed in an aqueous test medium which is either de-ionized water or water at pH 10, adjusted by adding Na_2CO_3 and $NaHCO_3$. The aqueous medium is changed every 2 weeks and the test basins are cleaned with 2% of orthophosphoric acid and de-ionized water. Alternatively one of the basins is equipped with an active carbon filter ensuring permanent water treatment.

Figure 3. Test setup and photos of test equipment (picture: BASt).

3.4.2 *Test procedure*

The test samples (plates 215 x 95 mm) are extracted from the middle of the product rolls. Samples for testing for MD and CMD are taken separately. The test samples for the immersion tests allow the die cutting of max. 3 test specimens type 5 (DIN EN ISO 527-3) for the tensile tests.

Prior to the immersion tests the GBR-P test samples are cleaned with de-ionized water and the surface weight and the thickness are determined. Test samples (one for MD and one for CMD) are removed from the immersion test after exposure for 24 hours (reference value without ageing), 30, 60, 120, 240, 360, 480 and 600 days. Two different temperatures and two different test media are investigated (see section 3.1). For all removed test samples the surface weight (after drying, see section 3.3), the tensile strength, the elongation at break and the E-modulus (see section 3.2) are determined.

4 RESULTS AND DISCUSSION

4.1 *Immersion tests*

The loss in weight due to migration of the plasticizer turned out to be very low (Fig. 4 and 5). Also the use of an aqueous medium at pH 10 does not influence the plasticizer loss considerably. For the different temperatures investigated there is only minor difference between the 60°C and 80°C results. Only the results for 85°C show a slightly higher loss in weight without a flattening of the curve. Also between the two different products no significant differences in the loss in weight could be determined. The longer the test samples are immersed in the test media the longer is the drying procedure which is required in order to measure the loss in weight. For storages of more than 360 days the drying procedure takes up to 192 hours, which is double the time required by DIN EN 14415. The results presented in Figure 4 and 5 show the loss in weight after complete drying according to DIN EN 14415, ignoring the limit of 96 hours drying time. The presented results are comparable to the results of Kramer et al. (2014), who also report about strong absorption of water after testing and only a small loss in weight after drying.

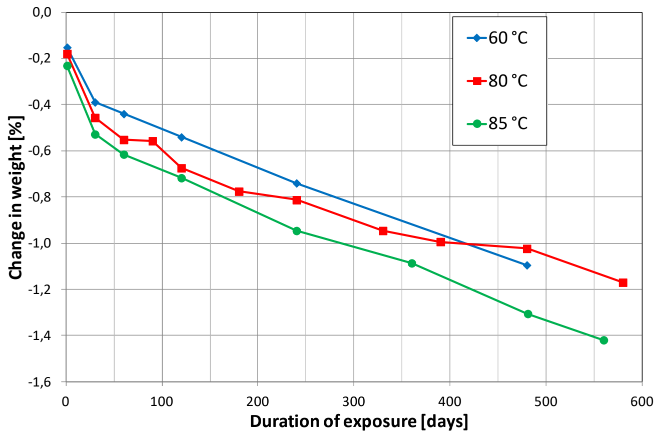

Figure 4. Change in weight of GBR-P product 1 after exposure in de-ionized water at different temperatures.

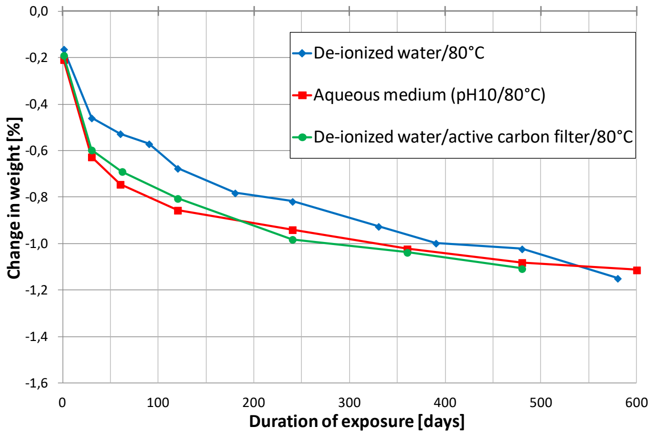

Figure 5. Change in weight of GBR-P product 1 after exposure in different media.

The tensile tests show a significant reduction of the elongation at break and a strong increase in the E-modulus after exposure to temperatures of 80°C and above. Figures 6 and 7 show the change in the elongation at break compared to the initial product characteristics presented in Table 1. Product 1 is more sensitive regarding the exposure conditions in the immersion tests (Fig. 6). Therefore this product was chosen for the further investigations regarding temperature and test media sensitivity. A higher test temperature of 80°C or 85°C lead to a significant degradation of the product whereas a test temperature of 60°C has no significant influence on the tensile characteristics of the product (Fig. 7 & 8). The investigations with a temperature of 85°C showed especially regarding the E-modulus a less severe influence on the products tensile characteristics (Fig. 8). Therefore the investigations regarding different test media were done at a test temperature of 80°C. The results concerning different test media show that the aqueous medium with pH 10 does not influence the elongation at break of product 1 more than the test with de-ionized water as the test medium. Regarding the E-modulus the investigations with de-ionized water showed the strongest influence on the products characteristics (Fig. 9). The tensile strength at break is generally not influenced significantly by the different exposures (neither temperature nor test medium) of the products. The results of CMD samples compared to MD samples are always a little bit worse. For that reason the following figures report only the CMD results. After assessing the different test conditions a good compliance of the here reported results of product 1 with the test results for the 'optimized NEAT GBR-P' in Kramer et al. (2014) could be found.

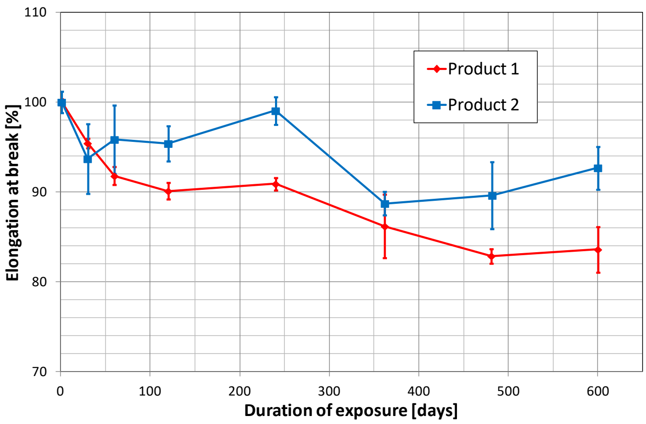

Figure 6. Change in the elongation at break of GBR-P products after exposure with pH 10 / 80°C (CMD).

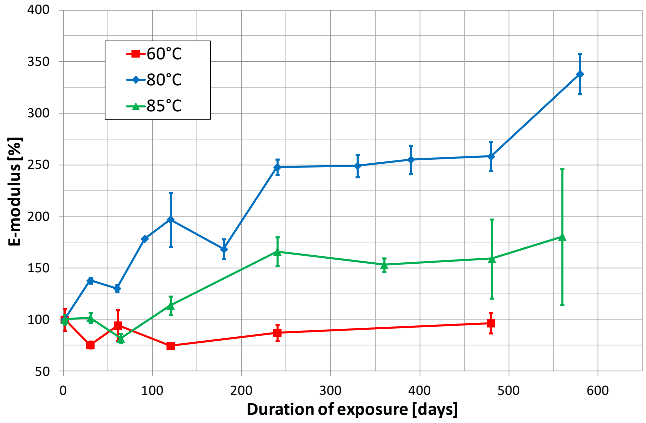

Figure 8. Change in the E-modulus of GBR-P product 1 after exposure in de-ionized water with different temperatures (CMD).

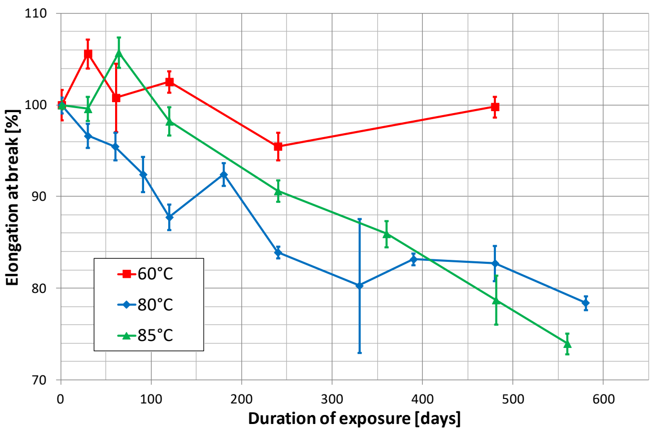

Figure 7. Change in the elongation at break of GBR-P product 1 after exposure in de-ionized water with different temperatures (CMD).

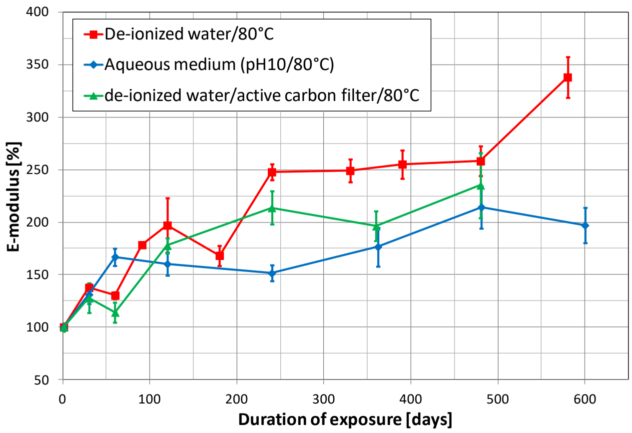

Figure 9. Change in the E-modulus of GBR-P product 1 after exposure in different media with a temperature of 80°C (CMD).

4.2 *In situ aged GBR-P*

4.2.1 *Mountain water samples*

The mountain water samples from the two tunnels were taken at different dates and different locations. The collecting pipe is located at the outside the tunnel near the portal (tunnel entrance) and the samples at the different cross passages (CP) were taken out of a drainage shaft inside the tunnel. The different mountain water samples show different temperatures and an alkaline pH-value (Table 2). The dissolved substances (mainly salts and metal ions) in the mountain water were determined but not reported here. The different mountain water temperatures could be explained by the different rock cover of the tunnels, seasonal variations and the location inside the tunnel (CP) or outside the tunnel (collecting pipe). Additional reasons could be found in local hydrogeological conditions (mechanical defects of the rock, entrance of seepage water from the surface, etc.).

When comparing with the test media used in the immersion tests the in situ exposure conditions of the GBR-P in tunnel sealing systems are much less aggressive in terms of temperature, but comparably aggressive in terms of chemical composition of the mountain water. The results of the mountain water analysis of the two tunnel presented in Table 2 also show the variable characteristics of the mountain water. There is no standard mountain water which could be used for accelerated ageing tests. For that reason the test media mentioned in 4.1 is chosen in order to simulate unfavorable conditions especially in terms of pH-value.

4.2.2 *GBR-P characteristics*

Many of the 30 and 23 years old PVC-based GBR-P samples taken from 2 different German road tunnels show local mechanical damages (e.g. indentations, see Figure 2). The mechanical properties are determined at specimens gained from as much as possible undamaged areas of the in situ taken samples. The results show generally a still high residual tensile strength and elongation at break (Table 3) but a clear increase of the residual E-modulus compared to the mechanical properties of new material (see Table 1). The requirements of the German standard ZTV-Tunnel part 1 (1995), which is the oldest standard defining minimum values for mechanical properties of GBR-P used in road tunnel sealing systems, are still fulfilled by the in situ aged GBR-P samples (requirements regarding the E-modulus did not exist at this time). The requirements of the current standard TL/TP KDB (2007) are also fulfilled by the investigated material samples, except the E-modulus which is clearly not meeting the requirements due to the loss in flexibility of the GBR-P. When comparing the results from the different sampling locations of Tunnel 1 and 2 significant differences in the mechanical properties could be discovered. There is not a single explanation responsible for these differences because there are so many influencing factors like local hydrological condition (e.g. fissure water), minor damage of the material (visually not detected) and influences from the GBR-P installation and construction.

The tensile strengths and the elongations at break of the 30 year old GBR-P are significantly smaller than of the 23 year old GBR-P. This result is in principle plausible as the exposure time in tunnel 1 is 7 years longer and the same product had been used in both tunnels. Due to different mountain water characteristics and amounts the exposure conditions in the two tunnels are different (see section 4.2.1) but basically comparable. The product used in both tunnels has the same product specification but the composition could have been changed by the manufacturer within the 7 years between the constructions of the two tunnels. Nevertheless the comparison of the results from tunnel 1 and 2 show that there is a significant trend to degradation of the PVC-based GBR-P products during in situ exposure which had been verified especially by the low residual flexibility of the in situ aged GBR-P, which was measured as increased E-modulus. These results clearly support the test results of the immersion tests. As the initial product characteristics of the material used in the two old tunnels could not be investigated an exact quantification of the degradation is not possible. The here presented results of the tensile tests are in good accordance with the results determined for material samples investigated by Beer et al. (2013) and Maehner & Lange (2008).

The thickness of the recovered in situ material samples is significantly lower than required by old and current standards (Table 3). A possible reason for that could be elongation of the GBR-P during construction of the inner concrete lining of the tunnel. Another reason could be of course a lower initial thickness of the product (initial characteristics are unknown). Investigations of Polyolefin-based GBR-P from old road tunnels also show, at least partly, such a reduction in thickness (Robertson et al. 2014).

The obvious local surface damages of the old GBR-P samples (Fig. 2) are not further discussed here. Indentations and local elongations as well as the remaining thickness in the indentations have been measured and will be reported in another publication at the end of this year (2018). The same applies to the results regarding the protection layer (geotextile). Possible explanations for mechanical damages can be found in Kaundinya (2012) and Robertson et al. (2014).

Table 2. Results of mountain water analysis.

Mountain water analysis	Tunnel 1 (30 years old)		Tunnel 2 (23 years old)			
	Date of sampling		Date of sampling			
	February 2012	July 2012	January 2012			July 2012
	Collecting pipe		Coll. pipe	CP6	CP7	Collecting pipe
In situ measurement						
Water temperature (°C)	7,8	17,9	10,4	6,9	6,6	17,1
pH-value	8,5	9,4	7,7	7,7	7,5	11,3
Conductivity (µS/cm)	-	300	897	553	507	890
Oxygen content (mg/l)	9,0	6,6	7,9	8,1	8,2	6,8

Table 3. Thickness and tensile properties (average values) and reference values from old and current standards.

Investigated samples / Requirements	Test standard	Thickness / mm	Tensile properties (CMD)		
			Tensile strength at break / N/mm²	Elongation at break / %	E-Modulus / N/mm²
Tunnel 1 (30 years old)					
cross passage 1 (3 samples)	DIN EN ISO 527-1 & -3, test specimen type 5, v=100 mm/min	1,86±0,01	18,2±1,8	363±60	56±10,4
cross passage 2 (4 samples)		1,91±0,03	18,8±1,0	391±38	31±6,5
cross passage 3 (3 samples)		1,87±0,01	18,8±0,4	304±25	24±1,4
cross passage 4 (2 samples)		1,88±0,02	19,1±0,7	398±13	22±6,8
cross passage 5 (4 samples)		1,90±0,02	19,1±0,3	430±11	23±4,5
cross passage 6 (2 samples)		1,86±0,02	16,6±0,4	262±3	20±6,3
Tunnel 2 (23 years old)					
cross passage 4 (1 sample)	DIN EN ISO 527-1 & -3, test specimen type 5, v=100 mm/min	1,77±0,02	20,7	379	45
cross passage 6 (4 samples)		1,90±0,02	21,3±0,5	496±20	22±4,5
cross passage 7 (3 samples)		1,70±0,03	25,6±0,4	378,±3	202±73
Old and current requirements					
ZTV-Tunnel (1995)	DIN 16726/5.6	≥ 2,0	≥ 10	≥ 200	None
TL/TP KDB (2007)	DIN EN ISO 527-1 & -3, test specimen type 5, v=100 mm/min	≥ 2,0	≥ 12	≥ 250	≤ 20

5 CONCLUSIONS AND OUTLOOK

This paper presents selected results of a completed research project dealing with the development of a new test procedure for assessing the durability of PVC-based GBR-P products in tunnel sealing systems. The developed immersion test based on the requirements defined in SIA V 280 standard (test no. 13) and DIN EN 14415 delivered plausible and reproductive results. Exposure conditions with 80°C, 360 days minimum exposure time and de-ionized water as the test medium turned out to be preferred in order to initiate significant accelerated degradation of PVC-based GBR-P materials. The investigations of the mechanical properties after ageing show a significant reduction of the elongation at break and a strong increase of the E-modulus but no significant changes in the tensile strength. The change in weight after ageing of the two different products investigated is found to be very small (less than 1.2% after 600 days) which is in contrast to the current limit value of 10% mentioned in the revised standard DIN EN 13491 (draft 2017). Additional investigations with a test temperature of 85°C for the immersion tests showed that a further increase of the test temperature is not necessary. The derived new test procedure including the obtained optimum test criteria was incorporated in the revision of the German regulations for road tunnel sealing systems (TL/TP KDB) which will be published end of 2017.

The investigation of GBR-P samples removed from older road tunnels showed no significant degradation of the tensile strength and elongation at break after 23 and 30 years of in situ ageing. Only a high E-modulus could be stated which is reflected by a low residual flexibility of the in situ aged samples. The requirements of old and current standards – except the requirements regarding the E-modulus - are still fulfilled by the in situ aged samples. With the help of mountain water samples, which have been taken at the same location and date as the GBR-P removal, the chemical and temperature exposure of the samples is determined. A distinct statement and quantification of the in situ degradation of the GBR-P products taken from two existing road tunnel sealing systems is not possible, because the original product characteristics could not be determined at the manufacturer or tunnel operator. The still good performance of the investigated GBR-P samples is also reflected by the status of these two tunnels with no significant leakages reported so far.

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