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**Research paper**

# Laboratory testing of selected prototype under sleeper pads (USPs) – pull-off strength determined after the weather resistance test

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**Abstract:** Under sleeper pads (USPs) are resilient elements used in the ballasted track structures to improve dynamic behaviour of the track, reduce vibration and protect the ballast against fast degradation. As the elements permanently connected to the sleepers or turnout bearers, the pads must have an appropriate level of pull-off strength, so that they do not separate from the rail support (here: sleeper) during their transportation to the construction site or during many years of operation. In this paper, results of pull-off tests performed on four selected USP samples are presented: three samples made of SBR (styrene-butadiene rubber) granulate and one made of polyurethane. Moreover, details of the pad's attachment to the rail support are discussed, and the requirements for the USP properties are specified, focusing on the pull-off strength determined after the weather resistance test. It is shown that only two out of four considered USP samples fulfilled the requirements specified by the authors.

**Keywords:** ballasted track structure, pull-off strength, under sleeper pad, laboratory testing of USP, weather resistance

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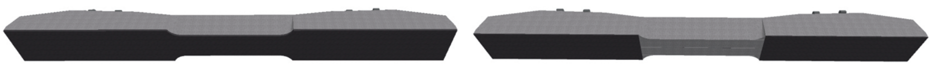
# 1. Introduction

Under sleeper pads (USPs) are vibration isolators used in the ballasted track structures to improve dynamic behaviour of the track systems. They provide protection against vibration, preserve the ballast under the tracks and improve the track stability [1,2]. USPs should be applied in the following cases:

- it is not possible to achieve a proper thickness of the ballast layer under the sleepers or turnout bearers, e.g. on civil engineering structures (bridges, tunnels) with a limited vertical alignment – in this case, the pads should protect the ballast against faster breakage;
- due to specific exploitation conditions, it is necessary to secure the track structure against faster degradation (such as track deformations);
- it is necessary to adjust stiffness of the track structure, mainly in transition zones;
- it is necessary to protect the built environment around the track system against high vibrations caused by its exploitation.

The pads are produced from elastomeric materials (usually 5÷20 mm thick), such as polyurethane (with closed or open pores) or rubber (blends of natural rubber and/or synthetic rubber) [3]. High elasticity of the rubber pads is assured by the shape (canals, channels and various insets) and structure (density and volume of the pores) of the pad's section.

USPs are installed at the bottom surface of the sleepers or turnout bearers in such a way, that they cover this surface either fully (Fig. 1a) or only the zone which actively transfers vertical loads (Fig. 1b) [4].



(a) (b)

Fig. 1. USP attached to the bottom surface of the sleeper: (a) full covering; (b) partial covering

Thanks to the variety of available USPs with different thicknesses and stiffnesses, they can be applied in the wide range of loads and train speeds, in various types of the ballasted track systems. Basic criteria for the selection of the specific pad variety include: maximum allowed rail deflection and eigenfrequency of vibration of the objects that should be protected against destructive influence of the vibrations caused by moving trains.

Various studies on resilient pads applied in the ballasted track systems can be found in the literature. Jayasuriya et al. [5] analysed performance of USPs which are aimed at reducing the ballast degradation and decreasing permanent deformation of the track. Neuhold and Landgraf [6] focused on long-term behaviour of the track with USPs. Guo et al. [7] studied mechanical performance of the ballast with and without USPs, demonstrating that the pads reduce the track stiffness and can decrease its settlement. Johansson et al. [8] analysed the influence of USPs on the dynamic train-track interaction. Omodaka et al. [9] proved that the subsidence of the track can be controlled using resilient pads. Abadi et al. [10] showed that the application of USPs can reduce maintenance requirements and whole-life costs for the track.

Paixão et al. [11] demonstrated that USPs applied at transition zones to railway bridges can reduce ballast degradation and control vertical stiffness of the track. Similar conclusions were drawn by Mottahed et al. [12], who conducted field tests on a transition zone to a railway bridge, where ballasted track equipped with USPs was applied.

At the Wrocław University of Technology, research on the impact of USPs on the performance of the track bed was conducted [13], which demonstrated their effectiveness in reducing negative effects of dynamic overloads. This efficiency is particularly noticeable for prestressed concrete sleepers with USPs, within the load frequency range of 16÷18 Hz, which corresponds to a travel speed of 140÷160 km/h. Research showed that the prestressed concrete sleepers with USPs can have damping properties similar to or even better than wooden sleepers. On railway lines with speeds above 160 km/h, the use of USPs would compensate for the increase in track stiffness and finally, would lead to extending the periods between repairs.

Sol-Sánchez et al. [14] studied USPs produced from end-of-life tires. Fatigue tests performed by the authors revealed that the tire pads are suitable for use in railway systems. Similar pads were investigated by Esmaeili et al. [15], who analysed how the pads of different thicknesses influence the ballast behaviour under cyclic loading.

In this study, the authors present results of laboratory pull-off tests performed on prototype USPs. In their previous works, they analysed fatigue strength [16] and resistance to severe environmental conditions [17, 18] of resilient elements. Here, the main focus is put on pull-off strength determined according to the procedure described in the European standard EN 1542 [19]. First, details of the attachment of USPs to the rail supports are discussed. Afterwards, requirements for the USP properties are specified, focusing on the pull-off strength determined after the weather resistance test. Authors' preliminary recommendations for the Polish railways PKP PLK S.A. are proposed, based on the review of the requirements of foreign railway infrastructure managers. Then, results of pull-off tests performed on USP samples made of SBR (styrene-butadiene rubber) granulate and PU (polyurethane) are presented.

## 2. Attachment of USP to the rail support

There are two ways of attaching USPs to the bottom surface of the rail supports – sleepers or turnout bearers – further referred to as supports:

– during the manufacturing process of the support – the pad is placed at the bottom surface of the support after the concrete mix has been compacted in the framework, and then the pad is pressed or vibrated in order to immerse the anchor layer of USP (e.g. geosynthetic) into the concrete mix;
– on the finished support – the pad is glued to the support with a fast-setting adhesive, and the process can be carried out either on the construction site (which is favourable,

as the USP is protected against potential mechanical damage that might occur during the transportation) or at the production stage.

Solutions for attaching USPs during the manufacturing process of the supports usually assume that the pads consist of three layers, described as follows (from top to bottom at the final operational position of the support):

– an anchor layer fixed in the concrete, which is usually a spatial element with protrusions penetrating the concrete of the support, for example made of plastic or geosynthetic;
– an elastic layer which is, from the point of view of the pad's function, its main layer made of an elastomeric material providing the pad an appropriate level of stiffness;
– a protective layer protecting the elastomer against mechanical damage caused by sharp-edged ballast grains, usually made from geosynthetic (the protective layer is not necessary).

Solutions designed to be attached to the bottom surface of the finished support with glue differ from the three-layer system described above in that they do not include the upper anchor layer fixed in the concrete of the support.

In USPs applied in different countries, the arrangement, material and structural layers of the pads are varied and do not result from the mandatory requirements of the European standards or other national regulations.

A French solution [20] consists in vibrating the USP (only the anchor layer) into the fresh concrete of the support. The pad made of polyurethane has a high adhesion, achieved by using various shapes of its protrusions (Fig. 2a–2c), which work in a similar way to anchors. Installation of such pads can be fully automated with specially made machines.

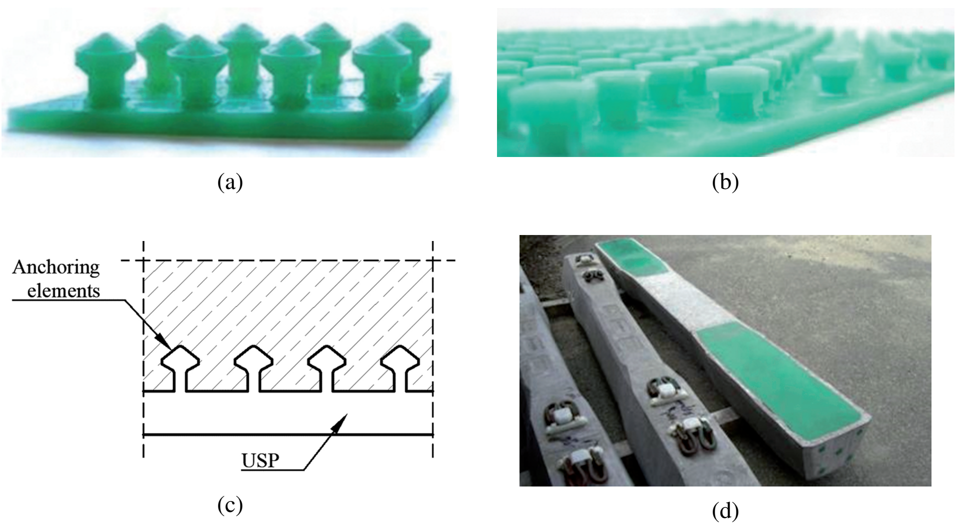



Fig. 2. USPs used on French railways: (a) anchor layer (protrusions with the upper surface in the shape of a "hat" [20]); (b) anchor layer (protrusions with a flat upper surface) [22]; (c) anchoring scheme; (d) location of USPs in the zone of an active transfer of vertical pressures [20]

USPs of this type can be used either along the entire length of the rail support or only in the zone of an active transfer of vertical pressures at the bottom of the rail support (Fig. 2d).

An Austrian solution [21] consists in placing the USP manually or by a machine on the unset concrete (Fig. 3d). Appropriate attachment of the pad to the support is ensured by gravitational loading of the pad and pressing it to the bottom surface of the support. The USP is made of polyurethane, and the anchor layer (anchoring spatial structure) resembles mesh connection (Fig. 3a–3c). Pads of this type are generally used along the entire length of the rail support. This solution enables the full automation of the assembly process of USPs.

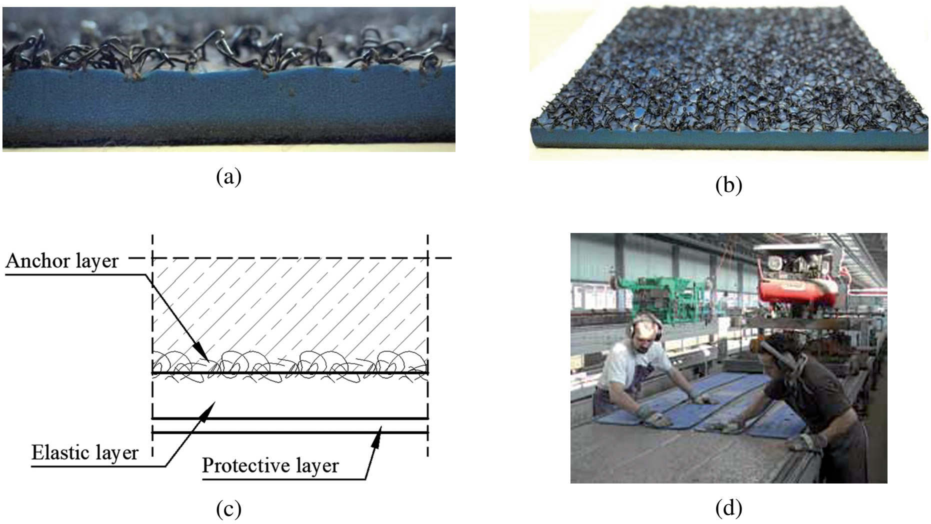



Fig. 3. USPs used on Austrian railways: (a) anchor layer – side view; (b) anchor layer – top view; (c) anchoring scheme; (d) placing USPs with an anchor layer on the unset concrete of the support [21]

A Korean solution [23] consists in placing the USP manually or by a machine on the unset concrete of the rail support (Fig. 4c). The pad is anchored in the concrete using special hook-like protrusions, which are immersed in the concrete in a way that prevents contact of the protrusions with the prestressed cables. USPs are made of polyurethane resin and used along the entire length of the rail support, with an expansion joint of 30 mm in the middle. The pads are 20 mm thick, and the 40 mm high protrusions are located 20 mm from the edge of the pad (Fig. 4a–4b). The protrusions have a hook and rectangular shape, they are placed alternately along the length of the pad, and there are orifices between the protrusions to prevent the formation of air voids around them and to ensure a flat surface of the pad (possible outflow of excess concrete mix).

Another French method consists in joining the USP with the support using aggregate [22], which is placed on the surface of the uncured polyurethane resin (Fig. 5a). The aggregate used in the pad consists of one fraction with a similar diameter to the diameter of the largest fraction in the concrete of the support, which ensures the greatest possible adhesion between the elements. This method consists in laying the USP on the unset con-

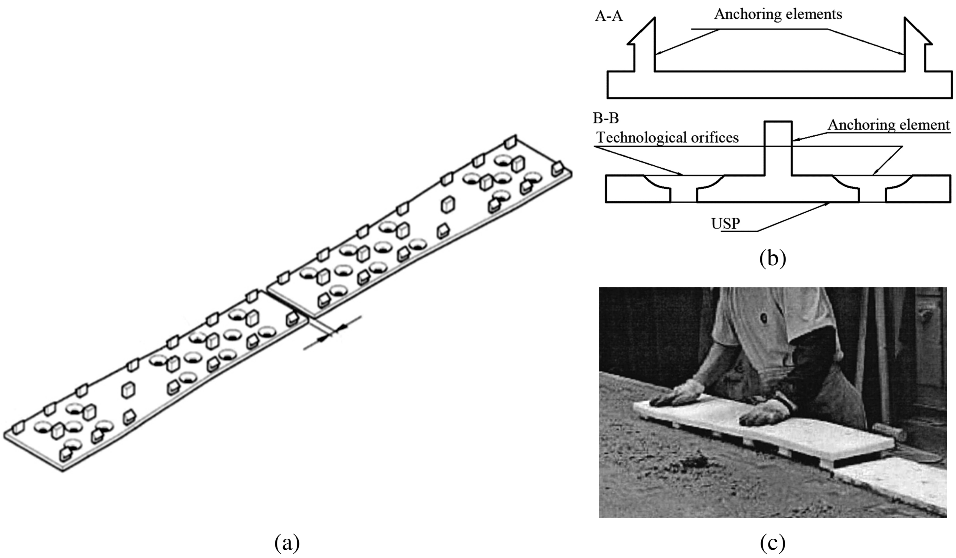



Fig. 4. USPs used on Korean railways: (a) anchor layer; (b) anchoring scheme; (c) placing USPs with an anchor layer on the unset concrete of the support [23]

crete of the support. The main disadvantage of this solution is an inhomogeneous stiffness of the pad across its cross-section (irregularly shaped aggregate penetrates the elastic layer of the pad to different depths) (Fig. 5b).

Attachment of USPs with an anchor layer in the form of special plastic protrusions (see Fig. 6) is also carried out on the unset concrete of the support. The shape of the protrusions ensures high adhesion of the pad to the bottom of the support. The anchoring elements are in the shape of elongated sticks with an elliptical cross-section. The pads are manufactured in such a way that the axes of the protrusions are approximately 13 mm apart and parallel

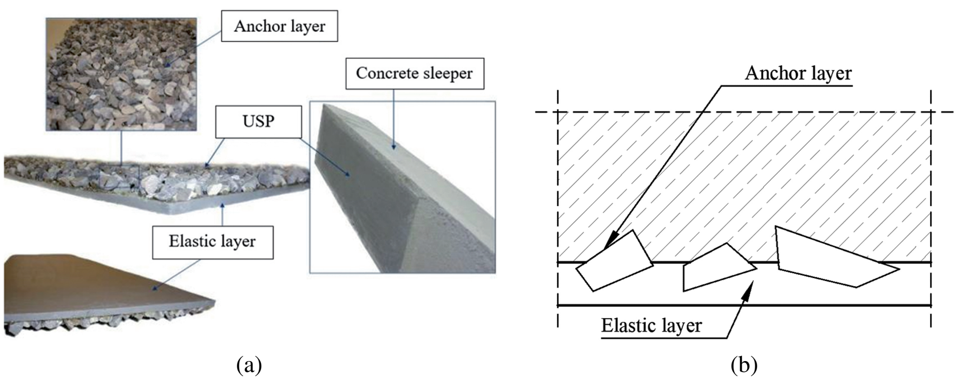



Fig. 5. USPs used on French railways: (a) details of the anchor and elastic layers of the pad [22, 24]; (b) anchoring scheme

to the longitudinal axis of the support. The anchor layer is connected to the elastic layer by an adhesive.

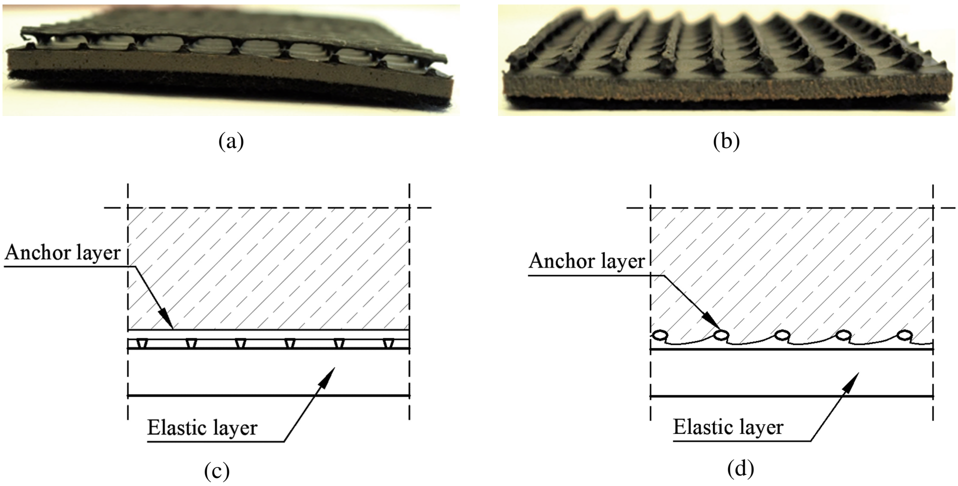



Fig. 6. USP with a plastic anchor layer: (a) view in the longitudinal direction; (b) view in the transverse direction; (c) anchoring scheme in the longitudinal direction; d) anchoring scheme in the transverse direction

As in the previous examples, attachment of the USP to the support using a geotextile anchor layer (Fig. 7) is carried out on the unset concrete of the support. Part of the anchor element is glued to the elastic layer made of rubber granules. The connection of the layers is realized by the penetration of the concrete mix into a geotextile structure consisting of compressed fibre networks, which, under the influence of moisture from the fresh concrete mix, increase their volume while loosening their structure.

A spray method of applying the USP [25], used on French railways, consists in spraying a synthetic polymer (which constitutes the pad) onto the bottom surface of the rail support (Fig. 8a and 8c). The sprayed polymer penetrates the structure of the concrete, which ensures the adhesion of the pad to the bottom surface of the support (Fig. 8b). This type of

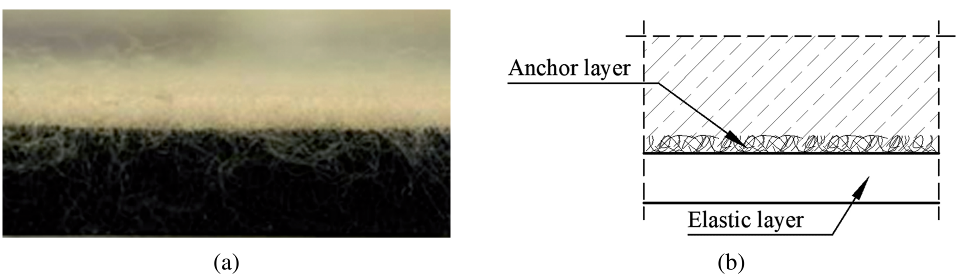
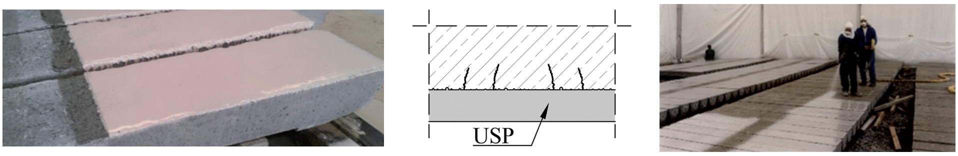



Fig. 7. USP with a geotextile anchor layer: (a) section view of the anchor layer (geotextile); (b) anchoring scheme

the pad's attachment ensures high water resistance as well as the ability to cover surfaces of various shapes, including uneven ones. This method can be used in prefabrication plants, where high automation of the production process of the supports with USPs is possible.




(a) (b) (c)

Fig. 8. USP attached to the support with a spray method used on French railways: (a) USP after spraying onto the bottom surface of the support [25]; (b) scheme of polymer penetration into the concrete structure to ensure proper adhesion of the pad to the support; (c) USP spraying process [24]

Another method of attaching the USP to the rail support consists in gluing the pad to the finished support using a fast-setting adhesive, e.g. epoxy adhesive (Fig. 9). The surface to which the pad will be attached must be dry and clean, it should be as smooth as possible (the rougher the surface, the more glue is required). Attachment of the USP is carried out as follows:

– the rail support is placed upside down and cleaned if necessary;
– glue is prepared (according to the manufacturer's instructions);
– the prepared adhesive is placed on the bottom surface of the rail support;
– the required amount of glue is determined by the roughness of the concrete surface and the size of the support (usually 0.5 to 2.0 kg of glue per element is used);
– the pad is placed centrally on the rail support;
– the pad should be pressed down evenly with a load of approx. 50 kg while the glue dries;
– after the bonding process, there should be no cavities that are not filled with glue;
– the total thickness of the adhesive layer should not exceed 5 mm, as it could affect negatively the stiffness of the connection.

(a) (b)

Fig. 9. USPs glued to the bottom surface of the supports: (a) prestressed concrete sleepers [26]; (b) turnout bearers [21]

In addition to typical applications USPs, they can also be used on wooden (Fig. 10a–10b) or steel (Fig. 10c) supports. In the case of wooden supports, the pads can also be installed using so-called staples.

(a) (b) (c)

Fig. 10. Wooden and steel rail supports: (a) USP attached to the wooden support; (b) wooden support with USP [21]; (c) steel support with attached USP (further visible concrete turnout bearers with USPs) [21]

## 3. Regulations and requirements

Based on the review of the requirements of foreign railway infrastructure managers, the authors prepared tabular comparisons of the limit values ??of parameters considered particularly important for the proper selection of vibration isolators used in the ballasted track structure. Particularly, the requirements imposed by the International Union of Railways UIC [27] were taken into account, and the regulations valid in Italy [28] and France [29], as they are based on the standard procedure of EN 16730 [30]. Moreover, preliminary recommendations for the Polish railways PKP PLK S.A. were formulated.

Table 1 contains the requirements and authors' recommendations with regard to the resistance to severe environmental conditions of USPs and their pull-off strength determined after the weather resistance test.

Table 1. Required parameters of USPs (tested according to various procedures) based on the requirements of foreign railway infrastructure managers and preliminary authors' recommendation for the Polish railways PKP PLK S.A.

| Property | | UIC [27]* | Germany [31] | Italy [28]* | France [29]* | Authors' recommendation |
|---|---|---|---|---|---|---|
| Resistance to severe environmental conditions | Appearance | no damage | – | no damage | no damage | no damage |
| | $\Delta C_{stat}$ | – | – | – | ≤ 15% | ≤ 15% |
| | $\Delta C_{dyn\ (5\ Hz)}$ | ≤ 15% | – | ≤ 15% | ≤ 15% | ≤ 15% |
| | Pull-off strength after the test [N/mm$^2$] | min ≥ 0.4 | min ≥ 0.3 | min ≥ 0.4 | min ≥ 0.6 | min ≥ 0.40 mean ≥ 0.45 |

# 4. Pull-off test

The USP as an element permanently connected to the sleeper or turnout bearer, regardless of the assembly technology, must have an appropriate level of pull-off strength, so that the pad does not separate from the rail support during its transportation to the construction site or during its many years of operation. If the required pull-off strength value is not ensured, it could lead to the detachment of USP from the sleeper (e.g. due to the action of water and frost) and, as a result, the pad could no longer fulfil its function, e.g. in terms of improving the geometric quality of the track or reducing vibrations. The name of the tested feature "pull-off strength" is consistent with the standard EN 1542 [19] which defines the test procedure.

The tests presented in this paper concern pull-off strength of USPs determined after the tests of resistance to severe environmental conditions (the weather resistance tests were presented in the previous work of the authors [17]). In order to take into account the influence of unfavourable weather conditions (water, frost, low and high temperatures) on the pull-off strength of the pads during its operation in a ballasted railway track, the samples were previously tested for resistance to weather conditions. The tests were carried out on four selected materials of prototype USPs – three materials based on SBR granulate and one based on PU:

– USP no. 1 made of SBR granulate, 9 mm thick, attached with glue;
– USP no. 2 made of SBR granulate, 12 mm thick, attached with glue (Fig. 11a);
– USP no. 3 made of SBR granulate, 7 mm thick, attached with geotextile anchor layer;
– USP no. 33 made of PU, 7 mm thick, attached with glue.

The pads no. 1, 2 and 3 differ in the production technology, thickness and density.

This work is based on the wider research performed within the BRIK InRaViS project, which included several dozen prototype elastomer materials. In this paper, the authors present results obtained for four selected and characteristic USPs differing, for example, in thickness, material type or method of fastening. Adopted numbers of samples result from the numbering used in the project, hence the PU-based pad has the number 33. The authors have decided to keep the adopted general numbering rule, so that it is possible to compare results presented in their various publications on resilient pads. According to the recommendations of UIC [27] from 2018, the USP thickness should be between 5 mm and 15 mm. The pads considered in this study have thicknesses between 7 mm and 12 mm, which is within the recommended range.

The main assumption of this article is to show that regardless of the type of material (rubber or polyurethane) or the method of attaching the pad (adhesive or anchor layer), a uniform test procedure should be used to verify its pull-off strength after the weather resistance test. Therefore, the considered USP samples have different thicknesses and different fixing methods are presented. In addition, minimum limiting values of pull-off strength are proposed, showing that they are realistic to achieve in laboratory tests, but not all materials and fixing methods are able to meet these requirements.

It should be highlighted that three out of four pads discussed in this paper are made of SBR, which is manufactured from recycled rubber from end-of-life tires. In the authors' opinion, vibration isolators based on recycled elastomers show potential for a wide

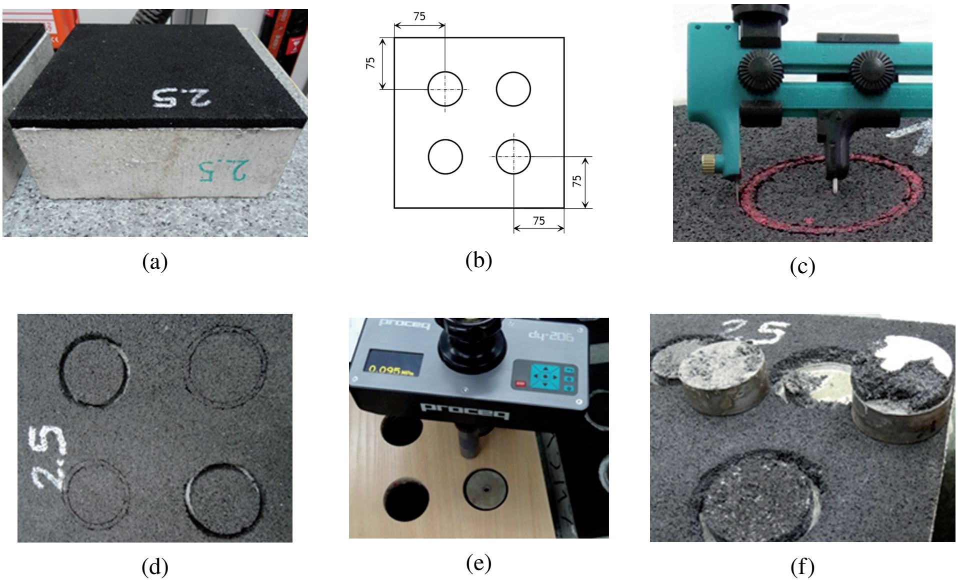



Fig. 11. Preparation of the USP samples and performance of the pull-off test: (a) USP glued to the concrete block; (b) arrangement of measurement points (according to EN 16730 [30]); (c) circle cuts in the USP material; (d) sample ready for gluing steel pull-off discs; (e) performance of the pull-off test using *Proceq dy-206*; (f) USP sample after the test, visible failure type

application in the construction of sustainable and environmentally friendly railway superstructures. The application of shredded rubber from recycled tires as a component of railway superstructures may be one of the most effective ways of managing rubber waste – while also fitting in with the European Green Deal policy.

All tested USP samples were previously (before the pull-off test) prepared for weather resistance testing in the manner specified in EN 16730 [30]:

– USP was mechanically glued or attached with an anchor layer to concrete block; after the adhesive has set (3–4 days) or 28 days after forming the concrete block (in the case of an anchor layer), samples of concrete blocks with USPs were kept in water for 24 h;
– after removal from the water, the samples were placed in a climatic chamber and subjected to cyclic freezing and thawing, which was aimed at simulating real atmospheric conditions in which the USP works.

It should be highlighted that due to the limited dimensions of the climatic chamber, it is not possible to perform such test on USPs attached to real sleepers (approx. 2.6 m long and weight approx. 320 kg). Therefore, the tested pads have smaller dimensions than the actual size of USPs used in track structures.

Pull-off tests (on samples after weather resistance test) were carried out according to the procedure described in EN 1542 [19]. According to this method, in each sample of the USPs, circles with a diameter of 50 mm were cut out (Fig. 11c and 11d), to which steel discs with a diameter of 50 mm were then glued. For each USP sample, the pull-off strength was measured at four points, the location of which was determined in accordance with Annex N to EN 16730 [30], i.e. at a minimum distance of 50 mm from the edge of the sample and the next measurement point. The layout of the measurement points is shown in Fig. 11b.

The pull-off strength expressed in N/mm$^2$ was measured using *Proceq dy-206* (Fig. 11e). The disc detachment speed, according to Annex E to EN 16730 [30], was constant and equal to 0.01 N/(mm$^2$s). After testing the material sample (Fig. 11f), the type of failure was determined according to the following criteria:

– cohesive failure in the layer of concrete block – type A;
– cohesive failure in the material layer – type: B, C, D, E, F, G, H;
– adhesive failure between adjacent layers – e.g. type B/C.

Results of pull-off tests are presented in Tables 2–5, graphs of changes in pull-off strength during the test – in Fig. 12, and the USP samples with visible failure after the test– in Fig. 13.

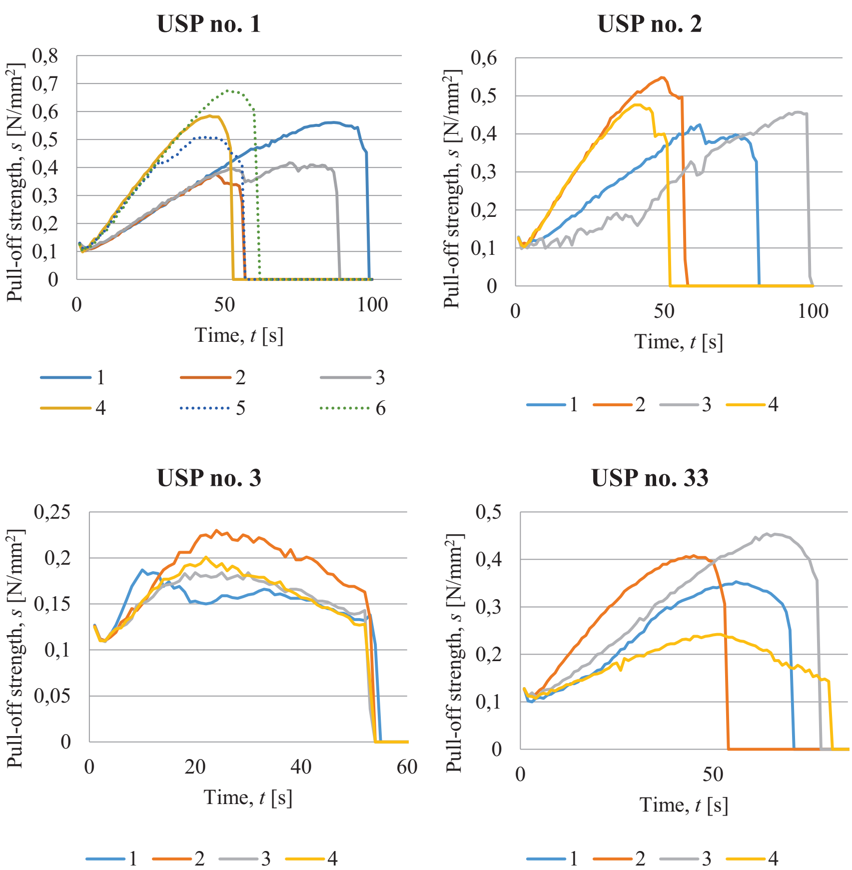
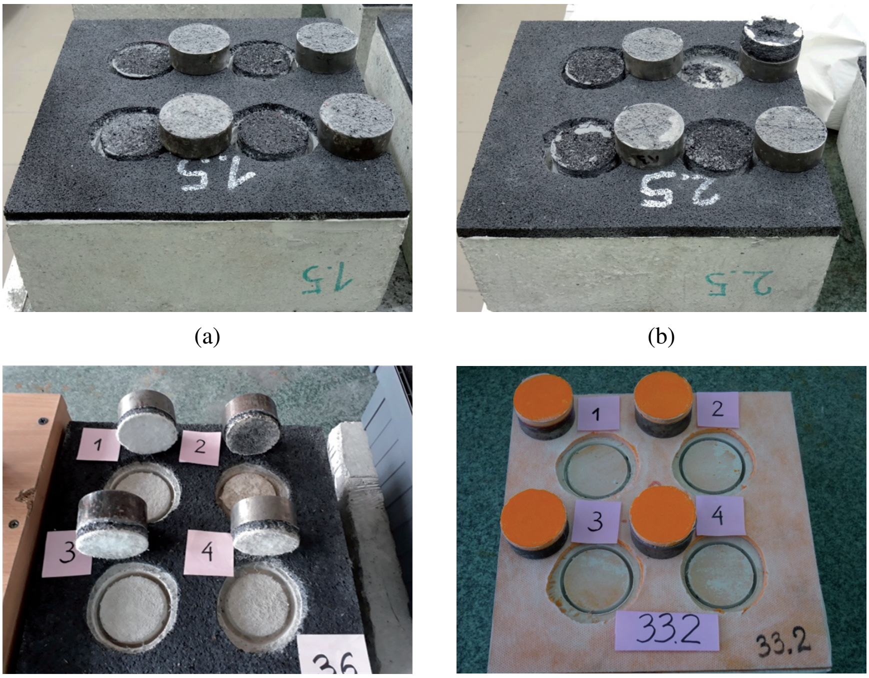



Fig. 12. Results of the pull-off test of four USPs – pull-off strength determined after the weather resistance test




(a) (b)

(c) (d)

Fig. 13. USP samples after the pull-off test – visible failures: (a) USP no. 1; (b) USP no. 2; (c) USP no. 3; (d) USP no. 33

Table 2. Results of the pull-off test of USP no. 1 – pull-off strength determined after the weather resistance test

| Disc no. | Pull-off strength, $s$ [N/mm$^2$] | Type of failure* | Layers |
|---|---|---|---|
| 1 | 0.57 | C/D | 0 – steel disc<br>D – epoxy glue 2<br>C – USP<br>B – epoxy glue 1<br>A – concrete block |
| 2 | 0.38 | C/D | |
| 3 | 0.42 | C/D | |
| 4 | 0.59 | C/D | |
| 5 | 0.52** | C/D | |
| 6 | 0.68** | C/D | |
| **Mean value** | **0.49** | **0.53*****  | |
| Standard deviation | 0.10 | 0.11*** | |

* **Failure type C/D** means that an adhesive failure occurred between the layer of glue that was used for gluing the steel disc and the elastomer of the pad.
** Discs glued again after pulling off discs no. 2 and 3 (the test continued till the minimum pull-off strength value was obtained – see authors' recommendations in Table 1).
*** Result taking into account additional data from re-pulling off the discs.

Table 3. Results of the pull-off test of USP no. 2 – pull-off strength determined after the weather resistance test

| Disc no. | Pull-off strength, $s$ [N/mm$^2$] | Type of failure* | Layers |
|---|---|---|---|
| 1 | 0.43 | C/D80%–D/020% | 0 – steel disc<br>D – epoxy glue 2<br>C – USP<br>B – epoxy glue 1<br>A – concrete block |
| 2 | 0.55 | C/D | |
| 3 | 0.46 | C/D | |
| 4 | 0.48 | C/D20%–A/B20%–C60% | |
| **Mean value** | **0.48** | – | |
| Standard deviation | 0.05 | – | |

* **Failure type C/D80%–D/020%** means that an adhesive failure C/D occurred between the layer of glue that was used for gluing the steel disc and the elastomer of the pad. At the same time, an adhesive failure D/0 occurred between the glue layer and the steel disc. The percentage of failure types was estimated.

**Failure type C/D** means that an adhesive failure occurred between the glue layer and the elastomer of the pad.

**Failure type C/D20%–A/B20%–C60%** means that an adhesive failure C/D occurred between the layer of glue that was used for gluing the steel disc and the elastomer of the pad. At the same time, an adhesive failure A/B occurred between the layer of glue that covered the concrete block and the material of the block. Additionally, a cohesive failure C occurred in the elastic layer (elastomer material) of the pad. The percentage of failure types was estimated.

Table 4. Results of the pull-off test of USP no. 3 – pull-off strength determined after the weather resistance test

| Disc no. | Pull-off strength, $s$ [N/mm$^2$] | Type of failure* | Layers |
|---|---|---|---|
| 1 | 0.19 | A/B | 0 – steel disc<br>D – epoxy glue 2<br>C – USP<br>B – epoxy glue 1<br>A – concrete block |
| 2 | 0.23 | B/C (A/B)** | |
| 3 | 0.19 | A/B | |
| 4 | 0.20 | A/B | |
| **Mean value** | **0.20** | – | |
| Standard deviation | 0.02 | – | |

* **Failure type A/B** means that an adhesive failure occurred between the layer of glue that covered the concrete block and the material of the block.

**Failure type B/C** means that an adhesive failure occurred between the elastomer of the pad and the layer of glue that covered the concrete block.

Remarks:
** Anchor layer partially detached from the USP (30%).

Table 5. Results of the pull-off test of USP no. 33 – pull-off strength determined after the weather resistance test

| Disc no. | Pull-off strength, $s$ [N/mm$^2$] | Type of failure* | Layers |
|---|---|---|---|
| 1 | 0.37 | B/C | 0 – steel disc<br>D – epoxy glue 2<br>C – USP<br>B – epoxy glue 1<br>A – concrete block |
| 2 | 0.41 | B/C | |
| 3 | 0.46 | B/C | |
| 4 | 0.24 | B/C | |
| **Mean value** | **0.37** | – | |
| Standard deviation | 0.09 | – | |

* **Failure type B/C** means that an adhesive failure occurred between the elastomer of the pad and the layer of glue that covered the concrete block.

# 5. Discussion and conclusions

In this study, the authors presented results of pull-off strength tests performed on four prototype USP samples: three pads made of SBR granulate and one made of PU. The tests were carried out according to the procedure described in EN 1542 [19] on samples previously submitted to weather resistance tests.

In addition, the authors proposed preliminary recommendations for the Polish railways PKP PLK S.A., which refer to the requirements of foreign railway infrastructure managers, particularly the ones imposed by the International Union of Railways UIC [27], and the regulations valid in Italy [28] and France [29], as they are based on the standard procedure of EN 16730 [30]. The following limiting value of pull-off strength determined after the weather resistance tests were proposed: minimum value $\geq 0.40$ N/mm$^2$ and average value $\geq 0.45$ N/mm$^2$.

This study focused only on the requirements with regard to pull-off strength of USPs measured after the weather resistance test. Other requirements (in relation to other significant parameters of USPs) have already been proposed or will be presented in future works (including the works of this research team), for example: fatigue strength was examined by Kraśkiewicz et al. in [16], longitudinal and transverse resistance of the track structure and its possible impact on the stability of the contactless track was analysed by Iliev in [3], vertical displacements were tested experimentally by Loy et al. in [32], and potential damage of the pads caused by sharp ballast grains was investigated by Kraśkiewicz et al. in [16] (ballast simulated with GBP) and by Sol-Sánchez et al. in [14] (real ballast). In future works, the authors plan to present results of the tests performed on SBR-based USPs with real ballast, taking into account possible variations in the parameters of the ballast used in the laboratory tests (e.g. grain size and density), what may have a significant impact on the obtained results (e.g. number and type of damage of the pads).

Comparing the results of laboratory tests presented in Fig. 12 and in Tables 2–5 to the proposed pull-off strength limits specified for USPs after the weather resistance test, it was found that only two of the four considered materials met those requirements – USPs no. 1 and no. 2. For the remaining two USPs (no. 3 and no. 33), further work on the adhesive and the anchor layer is required to improve the pull-off strength and reach the value for each single test of at least 0.40 N/mm$^2$ and an average value of at least 0.45 N/mm$^2$.

In addition to the values of pull-off strength, the authors also analysed types of occurring failures. In USP no. 1, there was an adhesive failure between the layer of glue that was used for gluing the steel disc and the elastic layer of the pad. In USP no. 2, four types of failures occurred: the one observed in USP no. 1, plus an adhesive failure between the glue layer and the steel disc, an adhesive failure between the layer of glue that covered the concrete block and the material of the block, and a cohesive failure in the elastic layer of the pad. In USP no. 3, two types of adhesive failures were observed: between the layer of glue that covered the concrete block and the material of the block, and between the elastic layer and glue covering the concrete block. In USP no. 33, an adhesive failure occurred between the elastomer and the layer of glue that covered the concrete block.

Adhesive failure A/B identified in two out of four tested samples indicates that the applied anchor layer, which was a part of the USP, did not exhibit enough adhesion to concrete. Therefore, the anchor layer should be changed to a different material (e.g. a different type of geotextile) – the prototype should be modified and the test repeated, until the required minimum pull-off strength is achieved. Similarly, failure type B/C indicates that the durability of the connection between the elastic part of the pad and its anchor layer should be improved. As it turned out, the proposed adhesive is not suitable for attaching USP no. 33 to the sleeper (e.g. directly at the construction site), as it does not provide the required value of pull-off strength. Another adhesive should be selected and further tests performed, in order to prove the durability of the connection of USP no. 33.

It should be highlighted that the same type of sleeper, e.g. PS-94, may be produced in various prefabrication plants and even if the applied concrete mix has similar parameters, the final product may differ depending on the local aggregate used, which may affect the pull-off strength value. Therefore, the test should be performed each time for the specific USP, its attachment method and sleepers prefabrication plant, where the pad may be glued in the future.

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# Badania laboratoryjne wybranych prototypowych podkładek USP – wyznaczanie przyczepności przez odrywanie po badaniu odporności na warunki atmosferyczne

**Słowa kluczowe:** odporność na warunki atmosferyczne, podkładka podpodkładowa, podsypkowa nawierzchnia torowa, przyczepność przez odrywanie, badania laboratoryjne USP

## Streszczenie:

Podkładki podpodkładowe (z ang. USP – *under sleeper pad*) to elementy sprężyste stosowane w konstrukcjach podsypkowych nawierzchni szynowej w celu poprawy pracy nawierzchni pod obciążeniami dynamicznymi, zmniejszenia drgań oraz ochrony podsypki przed szybką degradacją. Jako elementy trwale połączone z podkładami lub podrozjazdnicami, podkładki USP muszą posiadać odpowiednią wytrzymałość na odrywanie (przyczepność przez odrywanie), aby nie oddzieliły się od podpory szynowej podczas transportu na plac budowy lub w trakcie wieloletniej eksploatacji.

W artykule omówiono szczegółowo różne sposoby mocowania podkładek USP do podpór szynowych, zdefiniowano wymagania dotyczące właściwości USP, skupiając się na wytrzymałości na odrywanie wyznaczonej po badaniu odporności na warunki atmosferyczne, a także przedstawiono wyniki przeprowadzonych badań laboratoryjnych podkładek.

Autorzy przedstawili wyniki badań przyczepności przez odrywanie (ang. *pull-off)* przeprowadzonych na czterech wybranych próbkach USP: trzech z granulatu SBR (kauczuk styrenowo-butadienowy) i jednej z poliuretanu. Badania przeprowadzono zgodnie z procedurą opisaną w normie EN 1542 na próbkach poddanych wcześniej badaniom odporności na warunki atmosferyczne.

Ponadto autorzy zaproponowali wstępne rekomendacje dla polskich kolei PKP PLK S.A., które odnoszą się do wymagań zagranicznych zarządców infrastruktury kolejowej – w szczególności regulacji Międzynarodowego Związku Kolejowego UIC oraz przepisów obowiązujących we Włoszech i Francji, opierających się na normowej procedurze EN 16730. Zaproponowano następujące graniczne wartości przyczepności przez odrywanie wyznaczonej po badaniach odporności na warunki atmosferyczne: wartość minimalna $\geq 0,40$ N/mm$^2$ i wartość średnia $\geq 0,45$ N/mm$^2$.

Porównując wyniki badań laboratoryjnych przedstawionych w rozdziale 3 z proponowanymi granicznymi wartościami przyczepności przez odrywanie określonymi dla USP po badaniu odporności na warunki atmosferyczne, stwierdzono, że tylko dwa z czterech rozpatrywanych materiałów spełniały te wymagania – USP nr 1 i nr 2. Dla pozostałych dwóch podkładek (nr 3 i nr 33) wskazane są dalsze prace nad poprawą wartości przyczepności przez odrywanie (nad spoiwem i materiałem warstwy przylegającej do spodu podkładu), aby osiągnąć wartość dla każdej pojedynczej próby wynoszącą co najmniej 0,40 N/mm$^2$ oraz wartość średnią wynoszącą co najmniej 0,45 N/mm$^2$.

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