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EXPERIMENTAL RESEARCH ON FATIGUE STRENGTH OF PROTOTYPE UNDER SLEEPER PADS USED IN THE BALLASTED RAIL TRACK SYSTEMS

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The present paper discusses static and dynamic characteristics of various under sleeper pads (USP) that are to be used in the ballasted track systems as resilient vibroacoustic isolators. Four different USP samples were put to fatigue tests and static and dynamic bedding moduli were determined. The purpose of the tests, which were carried out up to 500 thousand load cycles, was to determine which USP have favourable and which unfavourable properties, taking into account their potential application as the elements used for energy dissipation and reduction of noise and vibration. The obtained results allowed the authors to indicate samples with a potential for further analysis and to reject those, which did not satisfy the adopted criteria.

Keywords: under sleeper pads, vibration damping, fatigue strength

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1. INTRODUCTION

Under sleeper pads (USP) are installed in ballasted track systems to act as auxiliary damping elements, preserve the ballast under the tracks and improve track stability [1,2]. They reduce dynamic effects that are transferred from the rolling stock through the rails, fastening elements, rail supporting structure (sleepers or turnout bearers) to the ballast.

Under sleeper pads are produced from elastomeric materials and, for the purpose of this paper, can be divided into two groups, basing on the type of material used: pads based on polyurethane (with closed or open pores) and rubber pads (blends of natural rubber and/or synthetic rubber). USP are fixed to the bottom surface of the sleepers or turnout bearers in two possible cover arrangements: full or partial (in the area of the main transmission of vertical pressure) cover of the sleeper's bottom surface. The pads are installed during the manufacturing process of the sleepers (or turnout bearers), either by placing them in the formworks prior to the concrete pouring or by gluing them to the already made sleepers (or turnout bearers) with the use of a fast hardening adhesive.

Due to a variety of available pads – with varying geometrical and mechanical characteristics – they can be used in a wide range of ballasted track systems, including the high-speed rail lines and lines with high axle loads. There are two essential criteria for selection of a certain type of under sleeper pads: the maximum value of the rail deflection and the natural frequency of the whole structure.

Under sleeper pads used in the ballasted track systems should fulfil the following functions:

- auxiliary vibration isolation – reduction of the impact of vibrations and secondary noise, including the protection against stray current;
- significant reduction of stress in the ballast layer by increasing the contact area between the sleeper and the ballast layer and, as a result, improving its sustainability and durability;
- increased technical lifespan – maintaining a long-term ability to fulfil above functions in real operating conditions, with maximum 15-25% (see Tab. 3) of variability of main parameters during the laboratory fatigue tests conducted under extreme operating conditions.

Various studies on the behaviour of rail pads and other resilient elements used in ballasted track systems can be found in the literature. A review of elastic elements designed for railway tracks is presented in [3]. It discusses various aspects related to track stiffness, noise, vibrations, geometry degradation etc. A laboratory study of the mechanical behaviour of selected elastic elements is presented in [4], where various configurations of the track section are analysed and solutions that reduce the track stiffness and increase the energy dissipation capacity are indicated. In [5] rail pads made of deconstructed end-of-life tires are analysed. The authors assessed the impact of pads thickness on their mechanical properties when subjected to loads that simulated a passing train. The end-of-life tires can also be used to produce a crumb rubber to be applied as elastic aggregates mixed with ballast particles [6]. This solution should reduce the ballast degradation and increase its capacity to dissipate energy. Another example are polymer reinforced ballast railway tracks, described in [7]. It was proven that the ballast reinforcement can significantly reduce the track settlements. The paper [8] presents a study on the vibration attenuation at rail joints using elastic USP installed under concrete sleepers. In [9] it was demonstrated that it is possible to control the subsidence of the track using the resilient under sleeper pads. In [10], on the other hand, it was established that the use of USP can result in reducing the maintenance requirements and whole-life costs for the track. The authors in [11] discussed the performance of USP in reducing ballast degradation and decreasing permanent deformation of the track. The works [12-18] focus on mechanical modelling of railway track systems with resilient elements used for noise and vibration damping.

2. STATIC AND DYNAMIC CHARACTERISTICS OF USP

One of the parameters that defines mechanical properties of under sleeper pads is a bedding modulus. Static and dynamic bedding moduli determine effectiveness of damping the vibrations transmitted to the environment. The values of static and dynamic bedding moduli can vary significantly, depending on the type and inner structure of the material, thickness of the pad, load value for which the bedding modulus is defined and load frequency (for dynamic modulus). The static bedding modulus reaches the values from ~0,02 N/mm^3 to ~0,35 N/mm^3. A low value of the bedding modulus of the under sleeper pad results in a significant shear deflection of the rail and the railway track.

The static and dynamic bedding moduli of under sleeper pads should be determined following the procedures described in the European Standard EN 16730 [19]. They are calculated as a ratio of the applied stress (load applied to the sample divided by its area) and the measured deflection of the tested sample. Bedding moduli show how much the USP sample deflects under the applied load. The lower the values of bedding moduli are, the better effectiveness of vibration damping can be achieved. However, the values cannot be too small due to the static deflections of the rail.

For the purpose of this paper, four different prototype USP were tested in accordance with the requirements of the mentioned standard:

- 001 – a styrene-butadiene rubber-based pad (SBR) glued with a polyurethane glue – 9 mm thick;
- 004 – a styrene-butadiene rubber-based pad (SBR) glued with a polyurethane glue – 9 mm thick;
- 005 – a styrene-butadiene rubber-based pad (SBR) with polyurethane chips glued with a polyurethane glue – 7 mm thick;
- 033 – a polyurethane-based pad – 7 mm thick.

The samples 001 and 004 are made of the same material but they differ in grain sizes and density. All tested USP samples had the same dimensions: 250 mm × 250 mm x thickness of USP, and they were mounted to the concrete block measuring 250 mm x 250 mm x 100 mm (Fig. 1). The tests were conducted at the room temperature. The load was applied using a geometric ballast plate (GBP), presented in Fig. 2, which transmitted loads to the pads mounted to the top surface of the concrete blocks. The samples were supported by non-deformable smooth steel plates with a sanding disc (K240 grit on a rigid linen backing cloth). The sample loading (both static and dynamic) was applied by the INSTRON 8802 hydraulic fatigue testing system. The deflections were measured with the use of four displacement inductive sensors (WA-T type by HBM) together with HBM's Spider8 data acquisition and signal conditioning system and dedicated software - Catman AP.

a) b)

Fig. 1. Examples of tested USP samples attached to concrete blocks: a) sample no. 001; b) sample no. 004 [source: authors' own photos].

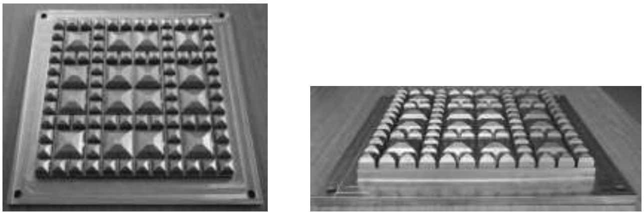


Fig. 2. Geometric ballast plates (GBP) used in the laboratory tests of USP [source: authors' own photos].

The static bedding modulus indicates deflection of the rail under the pressure of stationary rolling stock and has impact on the shear deflection of the railway track. It is calculated as a ratio of the stress to the unit deflection of the rail, measured under a uniaxial load. The relationship between the static bedding modulus and the applied force is non-linear. Therefore, the static bedding modulus should be determined within different ranges of load values, depending on the type of application (i.e. Track Category TC3).

The tests that are described in this paper concerned USP that can be used with concrete sleepers or bearers in Track Category no. 3 (TC3) according to EN 16730 [19], which includes:

- conventional main line railways with a typical axle load of 225 kN, a typical maximum speed of 200 km/h, a typical rail section of 60E1 and a typical sleeper or support spacing of 600 mm;
- lines with large radius curves, often used for high speed trains and having a typical axle load of 200 kN, a typical maximum speed of 320 km/h, a typical rail section of 60E1, a typical sleeper or support spacing of 600 mm.

The dynamic bedding modulus characterizes the pad's work under the pressure of moving rolling stock and therefore, it determines limitation of the vibration transmission. The value of the dynamic bedding modulus is related not only to the loading force, as in the case of the static bedding modulus, but also to load frequencies. The European standard EN 16730 [19] distinguishes two groups of testing procedures:

- for dynamic bedding modulus within lower frequencies $C_{\mathrm{dyn}}(f)$ (5, 10, 20 and 30 Hz);
- for dynamic bedding modulus within higher frequencies $C_{\mathrm{H}}(f)$ (10÷160 Hz).

The parameter $C_{\mathrm{dyn}}(f)$ can be used to determine the lower-frequency bending deformation of the rail under the influence of the rolling wheel, as a result of the interplay of the bending elasticity of the railway track structure. The parameter $C_{\mathrm{H}}(f)$ refers to under sleeper pads and can be used to determine the level of reduction of the structure-borne noise.

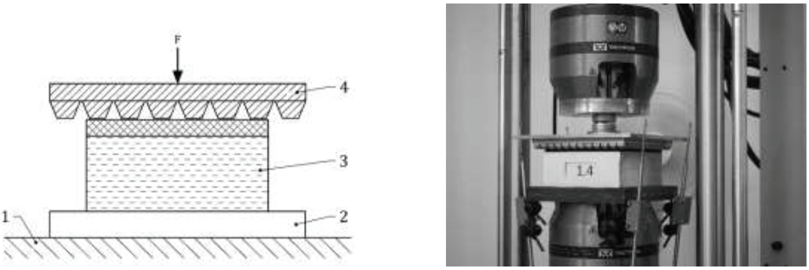
3. FATIGUE STRENGTH OF USP

The fatigue strength of USP is one of its most important parameters as it indicates the intended working life of the pad. The assessment of durability is crucial for determining the damping characteristics efficiency drop. It is important from the maintenance point of view as the replacement of the pads implicates major track repairs. Therefore, the fatigue strength of the pads should be taken into account while designing the railway track structure with USP. A low fatigue strength may reduce significantly the vibration damping capacity of the pads.

The durability of USP is evaluated through fatigue strength testing and the impact of the long lasting dynamic loading on the variability of the marked parameters. The test involves a three-stage dynamic loading of the pad on concrete block. Dynamic loads applied by a pulsator are sinusoidal with a frequency up to 15 Hz and are induced by a harmonic force (from 12 kN to 32 kN). They depend on: range of the values of static bedding modulus of tested USP; Track Category (TC); loading level (I - 2000 cycles; II – following 2000 cycles; III – following 3 million cycles).

Assessment of the under sleeper pad's durability includes a visual inspection of the sample (evaluation of damages, such as perforation, cracking etc.) and determination of the changes of the static and lower frequency dynamic bedding modulus at 5 Hz. The scope of the tests presented in this paper extended beyond the standard procedure of the USP assessment. For each sample three parameters were determined: C_{stat} - the static bedding modulus for the load range (0.01÷0.1) N/mm^2 C_{tend} - the static bedding modulus for the load range (0.01÷0.2) N/mm^2 and C_{dyn} - the dynamic bedding modulus for the load range (0.01÷0.1) N/mm^2 at 5 Hz. The samples were tested up to 500 000 cycles, which is lower than the mentioned 3 million, but was enough to determine which USP have good and which worse properties, taking into account their potential application in ballasted track systems as the elements used for energy dissipation and reduction of noise and vibration. The main purpose of the performed tests was to indicate samples with a potential for further analysis and to reject those, which did not satisfy the adopted criteria.

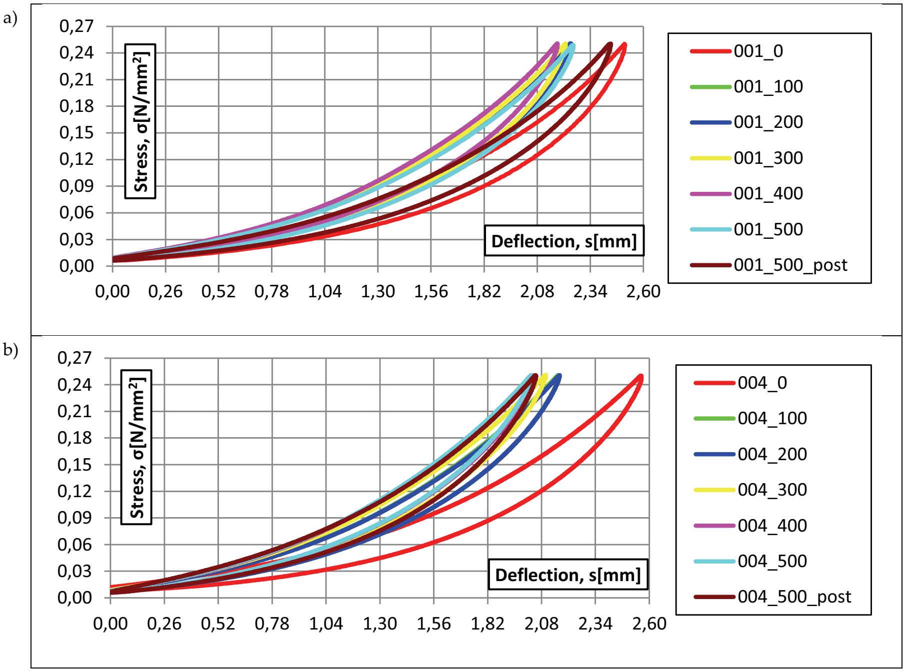
The standard EN 16730 [19] allows two variants of the USP fatigue testing procedure: with application of a steel ballast box or a geometric ballast plate. The tests described in this paper were conducted using the latter (Fig. 3).



a) b)

Fig. 3. Fatigue testing procedure: a) a scheme of the USP fatigue test (1 – non-deformable support, 2 – steel plate, 3 – USP on concrete block, 4 – GBP) [19]; b) sample no. 001 under test [source: authors' own photo].

The results of fatigue tests carried out on four USP samples are presented below. The static bedding modulus C_{stat} is depicted in Fig. 3, the low frequency dynamic bedding modulus C_{dyn} at 5 Hz obtained using the force control method – in Fig. 4. Each diagram contains five curves corresponding to: initial values (before fatigue testing), values after 100, 200, 300, 400 and 500 thousand cycles and values determined 1-2 weeks after the last fatigue test – marked "_post". Analysis of the curves allows to indicate which of the tested samples have favorable and which unfavorable properties. As it turned out, the polyurethane-based pad (sample no. 033) exhibits the best behavior taking into account its fatigue strength. In the case of this sample it can be noticed that the curves after relaxation are very close to the initial values, both for static and dynamic bedding moduli, which means that the sample had almost the same stiffness before and after fatigue tests. The rubber-based pad (sample no. 004), on the other hand, has the worst properties of four tested USP. In this case, the fatigue tests caused stiffening of the sample, which is an unfavorable effect for vibroacoustic isolators. Sample no. 001 can be considered as a rather good material, sample no. 005 should be rejected together with sample no. 004.



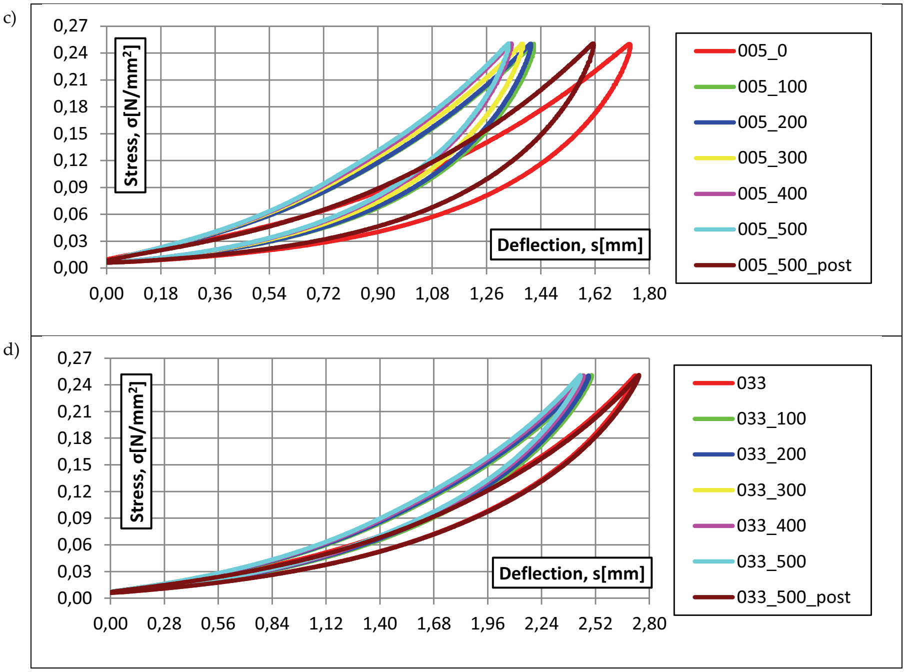
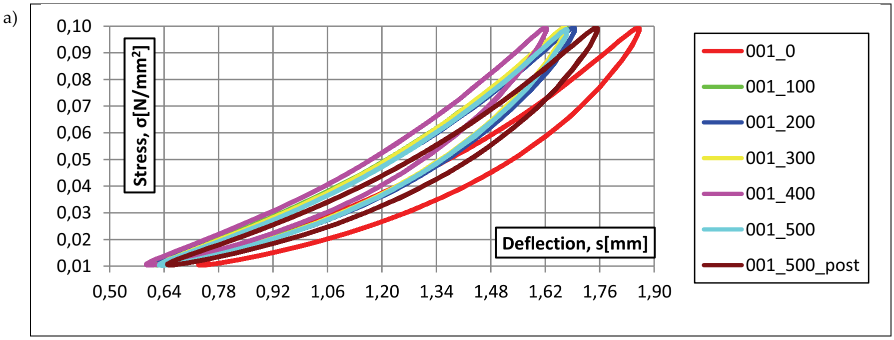


Fig. 4. Static bedding modulus obtained in fatigue tests for four USP samples: a) 001; b) 004; c) 005; d) 033.



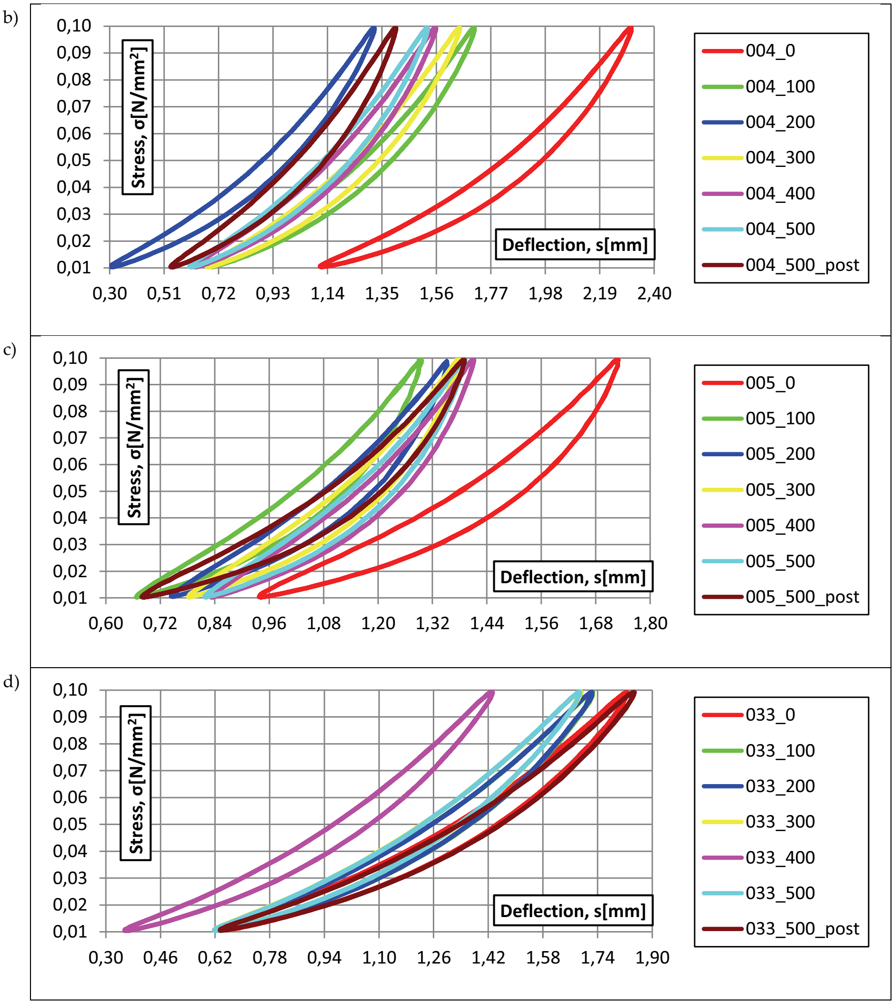


Fig. 5. Low frequency dynamic bedding modulus at 5 Hz for USP samples: a) 001; b) 004; c) 005; d) 033.

The values and variations of the static bedding moduli (for two load ranges) and the low frequency dynamic bedding modulus at 5 Hz obtained in the fatigue tests for four analyzed USP samples are given in Table 1. It can be noticed that the biggest change of stiffness values for all four tested samples occurs after 100 thousand load cycles, afterwards the stiffness variations reach much smaller values.

Table 1. Values of bedding moduli and their variations determined for four samples: 001, 004, 005 and 033.

Param.	**Bedding modulus [N/mm³]**													
	001_0	**Δ [%]**	**001_100**	**Δ [%]**	**001_200**	**Δ [%]**	**001_300**	**Δ [%]**	**001_400**	**Δ [%]**	**001_500**	**Δ [%]**	**001_500 _post**	**ΣΔ [%]**
C_{stat} (0.01-0.10)	0.059	11.9	0.066	0.0	0.066	1.7	0.067	1.7	0.068	-3.4	0.066	-10.2	0.060	1.7
C_{tend} (0.01-0.20)	0.086	10.5	0.095	-1.2	0.094	2.3	0.096	1.2	0.097	-3.5	0.094	-8.1	0.087	1.2
C_{dyn05}	0.079	7.6	0.085	-1.3	0.084	2.5	0.086	1.3	0.087	-2.5	0.085	-5.1	0.081	2.5
Param.	**004_0**	**Δ [%]**	**004_100**	**Δ [%]**	**004_200**	**Δ [%]**	**004_300**	**Δ [%]**	**004_400**	**Δ [%]**	**004_500**	**Δ [%]**	**004_500 _post**	**ΣΔ [%]**
C_{stat} (0.01-0.10)	0.054	29.6	0.070	0.0	0.070	5.6	0.073	7.4	0.077	0.0	0.077	-1.9	0.076	40.7
C_{tend} (0.01-0.20)	0.080	25.0	0.100	0.0	0.100	3.7	0.103	5.0	0.107	0.0	0.107	0	0.107	33.8
C_{dyn05}	0.075	17.3	0.088	0.0	0.088	5.3	0.092	5.3	0.096	2.7	0.098	6.7	0.103	37.3
Param.	**005_0**	**Δ [%]**	**005_100**	**Δ [%]**	**005_200**	**Δ [%]**	**005_300**	**Δ [%]**	**005_400**	**Δ [%]**	**005_500**	**Δ [%]**	**005_500 _post**	**ΣΔ [%]**
C_{stat} (0.01-0.10)	0.089	29.2	0.115	1.1	0.116	3.4	0.119	3.4	0.122	2.2	0.124	-32.6	0.095	6.7
C_{tend} (0.01-0.20)	0.124	25.0	0.155	0.8	0.156	2.4	0.159	3.2	0.163	1.6	0.165	-25.0	0.134	8.1
C_{dyn05}	0.114	24.6	0.142	3.5	0.146	3.5	0.150	4.4	0.155	1.8	0.157	-27.2	0.126	10.5
Param.	**033_0**	**Δ [%]**	**033_100**	**Δ [%]**	**033_200**	**Δ [%]**	**033_300**	**Δ [%]**	**033_400**	**Δ [%]**	**033_500**	**Δ [%]**	**033_500 _post**	**ΣΔ [%]**
C_{stat} (0.01-0.10)	0.055	12.7	0.062	0.0	0.062	3.6	0.064	-1.8	0.063	1.8	0.064	-18.2	0.054	-1.8
C_{tend} (0.01-0.20)	0.079	11.4	0.088	0.0	0.088	1.3	0.089	0.0	0.089	1.3	0.090	-13.9	0.079	0.0
C_{dyn05}	0.075	8.0	0.081	0.0	0.081	2.7	0.083	0.0	0.083	0.0	0.083	-13.3	0.073	-2.7

The total moduli variations between before (be) and after (af) each fatigue test were determined, using the formula [19]: $\Delta C_i = \left(C_{i,af} - C_{i,be}\right)/C_{i,be} \cdot 100\,[\%]$, where: i={stat; tend; dyn}.

4. REGULATIONS AND REQUIREMENTS

There are no valid regulations concerning the fatigue strength of under sleeper pads in Poland. Therefore, in order to assess the tested samples the requirements imposed by the following units were taken into account: the Italian Infrastructure Manager RFI, the German Railway Company DB AG and the Worldwide Railway Organization UIC (International Union of Railways).

The requirements imposed by various regulations on USP with regard to their fatigue strength are presented in Table 2.

Table 2. Requirements for USP with regard to the fatigue strength [22-25].

Regulation	Requirement	Tested parameter	Limiting value
DBS 918 145-01	Fatigue strength – fatigue test with USP on concrete block in the ballast*	Visual inspection	during and after the test: no perforations, cracks and other visible damages
RFI TCAR SF AR 03 007 C	Fatigue strength – fatigue test with USP on concrete block in the ballast**	Visual inspection	during and after the test: no perforations, cracks and other visible damages
		Static bedding modulus	$\Delta C_{\text{stat}} \leq 25\%$
		Dynamic bedding modulus	$\Delta C_{\text{dyn}}(5) \leq 15\%$
UIC 713-1	Fatigue strength – fatigue test with USP on concrete block in the ballast	Visual inspection	during and after the test: no perforations, cracks and other visible damages
		Static bedding modulus	$\Delta C_{\text{stat}} \leq 15\%$
		Dynamic bedding modulus	$\Delta C_{\text{dyn}}(4)$ or $\Delta C_{\text{dyn}}(10) \leq 15\%$
	Fatigue strength – fatigue test with USP on concrete block, with GBP***	Static bedding modulus	$\Delta C_{\text{stat}} \leq 15\%$
		Dynamic bedding modulus	$\Delta C_{\text{dyn}}(4)$ or $\Delta C_{\text{dyn}}(10) \leq 15\%$
IRS 70713-1	Fatigue strength – fatigue test with USP on concrete block in the ballast	Visual inspection	during and after the test: no perforations, cracks and other visible damages
	Fatigue strength – fatigue test with USP on concrete block, with GBP***	Visual inspection	during and after the test: no perforations, cracks and other visible damages
		Static bedding modulus	$\Delta C_{\text{stat}} \leq 15\%$
		Dynamic bedding modulus	$\Delta C_{\text{dyn}}(5) \leq 15\%$

*Test in the ballast box 1000x1000 mm; I load cycle = 5 million cycles, II load cycle = 3 million cycles (in total 8 million load cycles); frequency 3÷5 Hz

**Test in the ballast box min. 1000x1000 mm; 3 million load cycles; frequency 3÷5 Hz; test according to EN 16730, for TC3

***Recommended for soft USP

It can be noticed that two out of four tested USP samples fulfil the requirements listed above (sample no. 001 and 033). Sample no. 005 meets part of these criteria, however, taking into account the fact that the tests were performed up to 500 thousand load cycles instead of 3 million, this sample should be rejected together with sample no. 004.

5. DISCUSSION AND CONCLUSIONS

In the present paper static and dynamic characteristics of various prototype under sleeper pads (USP), that are to be used in the ballasted track systems as resilient vibroacoustic isolators, are discussed. Such elastic elements should provide protection against vibration, preserve the ballast under the tracks and improve track stability.

For the purpose of this paper four different USP samples were put to fatigue tests: two rubber-based pads differing in density, a rubber-based pad with polyurethane chips and a polyurethane-based pad. For each sample three parameters were determined: a static bedding modulus at the load range (0.01÷0.1) N/mm^2, a static bedding modulus at the load range (0.01÷0.2) N/mm^2 and a dynamic bedding modulus at 5 Hz. The samples were tested up to 500 000 cycles, which is lower than the required 3 million, but at the preliminary stage of verification was enough to determine which USP have favourable and which unfavourable properties, taking into account their potential application in ballasted track systems as the elements used for energy dissipation and reduction of noise and vibration. The main purpose of the performed tests was to indicate samples with a potential for further analysis and to reject those, which did not satisfy the adopted criteria.

In the fatigue tests seven states were taken into account: an initial state (before fatigue testing), states after 100, 200, 300, 400 and 500 thousand cycles and a state 1-2 weeks after the last fatigue test. The results of the performed analyses show that the polyurethane-based pad exhibits most favourable behaviour from the point of view of its fatigue strength. In the case of this sample it can be noticed that the curves obtained in the tests after relaxation are very close to the initial values, both for static and dynamic bedding moduli, which means that the sample had almost the same stiffness before and after fatigue tests. One of the tested rubber-based pads, on the other hand, exhibited the worst properties out of four considered samples– the fatigue tests caused stiffening of this sample, which is an unfavourable effect as far as the resilient vibroacoustic isolators are concerned. Further research will be carried out in order to improve the performance of rubber-based pads.

Analysis of the values and variations of the static bedding moduli (for two load ranges) and the low frequency dynamic bedding modulus at 5 Hz obtained in the fatigue tests lead to the conclusion that the biggest change of stiffness values for all four tested USP samples occurs after 100 thousand load cycles, afterwards the stiffness variations are much smaller.

The presented results can be used to calibrate a mechanical model of a ballasted railway track system with vibroacoustic isolators. Apart from the parameters discussed in this paper, the authors determined dynamic bedding moduli at various load frequencies (1-24 Hz) for each sample.

All these results can be used to obtain the amplitude-frequency characteristics of a mechanical model and the diagrams of transmissibility and insertion loss. Analysis of such diagrams allows to determine ranges of effective damping of vibration and noise. Moreover, using the obtained data a proper system of vibration and noise reduction can be designed, which would reduce the amplitudes in the vibroisolated system compared to the reference one, with no vibroisolating elements. Currently, the authors of the present paper focus on developing original rheological systems, which would simulate the viscoelastic behavior of vibroacoustic isolators taking into account degradation effects. Rheological systems will contain, apart from classic elements, also some non-typical elements described by a fractional order derivative. Preliminary, simplified examples of such models developed by the authors are presented in their previous works [12,13].

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LIST OF FIGURES AND TABLES:

BADANIA LABORATORYJNE WYTRZYMAŁOŚCI ZMĘCZENIOWEJ PROTOTYPOWYCH PODKŁADEK PODPODKŁADOWYCH USP STOSOWANYCH W PODSYPKOWYCH KONSTRUKCJACH DRÓG SZYNOWYCH

STRESZCZENIE

W niniejszej pracy omówione zostały statyczne i dynamiczne własności różnych prototypowych podkładek podpodkładowych (USP), które są stosowane w podsypkowych konstrukcjach dróg szynowych jako sprężyste tłumiki wibroakustyczne. Zadaniem tego typu elementów sprężystych jest zapewnienie ochrony przeciwko drganiom, zabezpieczenie podsypki pod torami i poprawa stabilności toru.

Na potrzeby tej pracy przeprowadzono badania wytrzymałości zmęczeniowej czterech różnych próbek USP: trzech podkładek na bazie granulatu gumowego o różnych własnościach oraz podkładki na bazie poliuretanu. Dla każdej z próbek wyznaczono trzy parametry: statyczny moduł sztywności dla obciążenia z zakresu (0.01÷0.1) N/mm^2, statyczny moduł sztywności dla obciążenia z zakresu (0.01÷0.2) N/mm^2 i dynamiczny moduł sztywności dla różnych częstotliwości obciążenia (1-24 Hz). Badania były prowadzone do 500 000 cykli obciążenia, co jest wartością mniejszą niż zalecane 3 mln, ale wystarczającą na wstępnym etapie badań do wskazania próbek USP o korzystnych i niekorzystnych własnościach, biorąc pod uwagę ich potencjalne zastosowanie w podsypkowych konstrukcjach dróg szynowych jako elementów służących do redukcji drgań i hałasu. Głównym celem przeprowadzonych testów było wskazanie próbek do dalszych badań i odrzucenie tych, które nie spełniają żądanych kryteriów.

W badaniach wytrzymałości zmęczeniowej analizowano siedem stanów: stan początkowy (przed badaniem), stany po 100, 200, 300, 400 i 500 tys. cykli obciążenia oraz stan po 1-2 tygodniach od wykonania badania. Wyniki przeprowadzonych badań pokazują, że najkorzystniejsze własności z punktu widzenia wytrzymałości zmęczeniowej wykazuje próbka na bazie poliuretanu. W przypadku tej próbki można zauważyć, że krzywe otrzymane z testów po relaksacji leżą bardzo blisko krzywych początkowych, zarówno w przypadku statycznego jak i dynamicznego modułu sztywności, co oznacza, że próbka miała prawie taką samą sztywności przed i po badaniu. Z kolei jedna z próbek na bazie granulatu gumowego wykazała najgorsze własności z czterech testowanych próbek – w wyniku badania próbka znacznie się usztywniła, co jest niekorzystnym efektem w przypadku sprężystych elementów wibroizolacyjnych. Planowane są dalsze badania, mające na celu poprawę charakterystyk próbek na bazie granulatu gumowego.

Analiza wartości i zmian statycznych (dla dwóch zakresów obciążenia) i dynamicznych (dla 5 Hz) modułów sztywności, otrzymanych w badaniach wytrzymałości zmęczeniowej, prowadzi do wniosku, że największa zmiana sztywności dla wszystkich czterech próbek następuje po 100 tys. cykli obciążenia, kolejne zmiany sztywności są znacznie mniejsze.

Otrzymane wyniki mogą zostać wykorzystane do kalibracji modelu mechanicznego podsypkowej konstrukcji drogi szynowej z tłumikami wibroakustycznymi. Korzystając z obszernych analiz zaprezentowanych w niniejszej pracy, możliwe jest wyznaczenie charakterystyk amplitudowo-częstotliwościowych dla modelu mechanicznego i otrzymanie funkcji przenoszenia drgań i tłumienia dodanego. Analiza tego typu wykresów pozwala na wyznaczenie zakresów efektywnego tłumienia drgań i hałasu. Ponadto otrzymane dane mogą posłużyć do zaprojektowania odpowiedniego systemu redukcji drgań i hałasu, który pozwalałby na zmniejszenie amplitud w stosunku do systemu referencyjnego bez tłumików. Obecnie autorzy pracy skupiają się na rozwinięciu oryginalnych systemów reologicznych, które symulowałyby lepkosprężyste zachowanie tłumików wibroakustycznych, biorąc pod uwagę efekty degradacji. Systemy reologiczne będą zawierały, oprócz klasycznych elementów, pewne nietypowe elementy opisane pochodnymi cząstkowymi.

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