Long-term properties of Sylomer® ballast mats installed in the rapid transit railway tunnel near the Philharmonic Hall of Munich, Germany

In 1983, ballast mats of type Sylomer® B 851 from Getzner Werkstoffe GmbH were installed in a rapid transit railway tunnel near the Philharmonic Hall of Munich, Germany, in order to shield it from the structure-borne noise emitted from the passage of trains. In 2001, after 18 years of use under extremely demanding load conditions, tests were conducted to determine the long-term effectiveness of the noise mitigation measure adopted, the results of which are presented in this article.

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At the beginning of the 1980s, the cultural centre “Am Gasteig” was built in the immediate vicinity of one of the main rapid transit railway lines in Munich, Germany. Besides other facilities, it houses a concert hall for the philharmonic orchestra and the municipal library (Fig. 1).

In order to shield, in particular, the concert hall from the structure-borne noise emitted from the rapid transit railway tunnel, which features very dense traffic, appropriate measures had to be taken to ensure that the background noise level in the concert hall did not exceed the specified limit of 25 dB(A), even when trains were running through the tunnel and, thus, also ensuring that the hall could be used for recordings [1]. Measurements taken at the site of the concert hall, and respective calculations, showed that a remarkable reduction in vibration levels in the frequency range of approx. 31 Hz – 200 Hz had to be achieved [2] (see also [3]).

Of the solutions that were discussed at that time, i.e. a room within a room construction, a 20 m deep slot with an elastic filling between the building and the railway tunnel, or the installation of ballast mats in the tunnel, the last measure was adopted.

At night, whilst the trains were not running, ballast mats of type Sylomer® B 851 were installed in the two tunnel tubes over a length of 345 m, using a specially developed procedure [4]. The ballast mats were designed for the load conditions of the rapid transit system, featuring a bedding modulus of 0.02 N/mm³ in accordance with [5].

The results from measurements of the structure-borne noise, carried out in both tubes of the tunnel before and after installation of the ballast mats, and at the construction site of the concert hall during the passage of trains, showed a very good consistency with the insertion loss values predicted using a “single-degree-of-freedom (SDOF) model” [6], [7], and completely met the requirements according to [1]. It should be noted that to date, as will also be shown in this article, no changes in the effectiveness of the adopted mitigation measure have been detected.

Over the past twenty years, ballast mats have been employed with similarly good results at many locations, both during the construction of new lines and - as has become increasingly common in the recent past – during the retrofitting of existing lines [8]. Just to cite a couple of examples, one need only to review the highly successful measures implemented in the rapid transit railway tunnel in the Chorweiler district of Cologne [9], or those realised in the Friedrichstraße station of the Berlin rapid transit system [10].

Despite the very good results and experience gained with ballast mats, and the much stricter testing requirements for determining the functional suitability of ballast mats as per [11], which have been adopted in the meantime, as compared to [5] (e.g. the fatigue strength tests must now be carried out with 12.5⋅10⁶ load cycles, instead of the earlier 2⋅10⁵ load cycles) and also due to ever keener international competition, customers are increasingly requesting additional evidence of the long-term functional suitability of the products installed (it should be noted that already since the mid-1990s all ballast mats offered by Getzner Werkstoffe GmbH have been meeting the stricter requirements as per [11]).

The rapid transit railway line near the Philharmonic Hall at the cultural centre “Am Gasteig” in Munich, which daily carries about 150,000 load tons, is one of the most heavily used rapid transit lines in Germany. Thus, it is a good location to investigate the long-term properties of Sylomer® ballast mats, taking the type B 851 as an example.

Since their installation in 1983, the ballast mats have been exposed to more than 760⋅10⁶ load tons. With the Class ET 420 multiple unit trains that are operated on the line featuring an axle load of 160 kN, this represents a fatigue load of more than 45⋅10⁶ load cycles, which is almost four times the value required according to [11] as a prerequisite for
approval for installation in track operated by German Rail (DB AG).

This article presents the results of laboratory tests that have been carried out on samples of ballast mat removed from the tunnel to determine the static and dynamic parameters of the Sylomer® B 851 ballast mat, and of vibration measurements carried out in the tunnel during the passage of trains to determine the long-term efficiency of the ballast mats installed.

The track in the tunnel is of the type K 54 1667 H, i.e. rail fastening K (rail clip), rail S 54, wooden sleepers with a spacing of 600 mm, and a ballast height of \( \leq 350 \text{ mm} \). Class ET 420 multiple unit trains are operated on the line which, as noted earlier, feature an axle load of 160 kN. The maximum speed operated in the tunnel area under study is 80 km/h.

**Laboratory tests**

In December 1999, after almost 17 years in operation, samples of the Sylomer® B 851 ballast mat were removed from the south tube of the rapid transit tunnel near the Philharmonic Hall of Munich, at the request of Getzner Werkstoffe GmbH, and under the supervision of DB AG, in order to examine the long-term properties of this product.

Two ballast mat samples, each featuring a dimension of approx. 600x1200 mm², were removed from the middle of the sleeper spacing to the neighbouring one and from the beginning of the load area at the sleeper end to the centre of the sleeper, from two different areas of track (see Fig. 2, 3):

- Area 1: normal ballast thickness, track curve,
- Area 2: extremely small ballast thickness, tangent track.

An optical / visual inspection of the samples, a determination of their static stiffness, and a comparison with the parameters specified in the quality control report prepared when the ballast mats were installed in 1983, were carried out by the Technical University of Munich - Prüfamt für Bau von Landverkehrswegen [12].

Analyses for determining the dynamic stiffness of the materials were carried out on a test-rig by Müller-BBM GmbH, Planegg near Munich [13].

**Visual inspection**

Since in both areas of removal the ballast mats were submerged in water on the tunnel floor (see, for instance Fig. 4), the samples had to be dried before testing, in order to have test conditions comparable to those during the tests that were carried out before installation of the ballast mats in 1983.

As pointed out in [12], imprint marks caused by the ballast grains were clearly visible on the surface of the ballast mats. The load distribution layer, i.e. the protection layer in the ballast contact area, was in very good condition. It showed slight plastic deformations, but no damage (for example, perforations). The pattern of the imprint marks caused by the ballast showed that the ballast grains were very well embedded in the surface of the ballast mat. The resilient layers were completely intact as well.

**Static stiffness**

The static load deflection curve in the load range up to approx. 0.25 N/mm² was determined for a piece taken from each of the two samples, each with a dimension of 300x300 mm², at a test speed of 0.16 kN/s [12]. In accordance with the special requirements (which deviate from those found in [5]) that were established in the tender documentation for the mitigation measure in 1983, a bedding modulus \( c_{\text{actual}} \) was determined, based on the load deflection curve for both samples, which was then compared with the nominal value of \( c_{\text{target}} \pm 12.5\% \) specified in the tender documentation.

The analysis indicated that the average bedding modulus obtained from the measurements carried out on the two samples was in the range \( c_{\text{actual}} = c_{\text{target}} + 10\% \), i.e. the nominal value requirements from the original tender documentation were still complied with even after the mats had been subject
to extremely demanding load conditions during their 17 years of use.

Dynamic stiffness

The dynamic stiffness of a ballast mat sample was determined using the so-called ‘direct method’ as per ISO 10846-2 [14], with the boundary conditions specified in [5]. Execution of the measurements and the results obtained are presented in [16]. Fig. 5 depicts a schematic diagram of the testing equipment employed, and Fig. 6 shows a picture of the corresponding test-rig used by Müller-BBM GmbH. The sample (4) was pre-loaded to the respective amount of static load using the load sensing platform (5) and the hydraulically adjustable traverse (2) with the pre-load unit (3). Application of the alternating force was effected with an electrodynamic shaker (1). The dynamic stiffness of the sample material was determined from the transfer function derived from the vibration velocity measured on the topside of the sample material and the alternating force transmitted into the foundation (6, 7).

Fig. 7 shows an example of the results of a measurement carried out as per [16], with a static pre-load level of 0.06 N/mm², which is characteristic for operation of rail rapid transit systems as per [15]. The sample used in this case had a dimension of 200x200 mm². For the purpose of comparison, Fig. 7 also shows the results of the original measurements carried out on three samples of ballast mat before installation in 1983 [17].

It is evident that the stiffness results for the recently removed sample are somewhat higher than those obtained for the samples at the time of installation. In this respect, however, it should be noted that, due to cost considerations (railway operating conditions in the tunnel, etc.), the recently removed samples could only be taken from two very restricted areas. Also, quality control regulations for ballast mats allow for deviations of ±15% from the required nominal value. Furthermore, as noted earlier and illustrated in Fig. 4, the recently removed ballast mat samples were submerged in water on the tunnel floor. The results, however, indicate that the presence of water did not have any significant impact on the long-term functional properties of the Sylomer® ballast mats.

On the whole, based on the results presented in Fig. 7, it can be said that no serious changes in the dynamic load deflection properties of the Sylomer® B 851 ballast mats had occurred during the 17 years of use under extremely demanding load conditions. Consequently, it was expected that, given similar boundary conditions in the tunnel (types of vehicle operated, rail running surface, track stiffness, etc.), a similar level of efficiency of the mitigation measure would be determined from the vibration measurements that were going to be carried out in the tunnel during the passage of trains, as was found after the mats were installed in 1983.

Vibration measurements during the passage of trains

Following completion of the laboratory analyses, one key aspect of the studies on the long-term properties of the Sylomer® B 851 ballast mats was to carry out measurements of structure-borne noise during the passage of trains in the tunnel at the ‘historical’ measuring points, i.e. those used at the time of installation in 1983. By comparing the results of the new measurements with those obtained immediately before and after installation of the ballast mats in 1983, it is possible to determine the vibration isolation efficiency of the ballast mats after long-term use under demanding load conditions.

Measurement boundary conditions

In order to obtain reliable and meaningful results, it was crucial that all parameters that are of influence on the generation of structure-borne noise in the measurements were the same as those at the time of previous measurements, or at least comparable to the extent technically possible. In this respect, the smoothness of the rails or, more specifically, the condition of the rail running surface is of great importance.

In the summer of 2000, in preparation for the measurements, an inspection of the condition of the rail running surface was carried out in the relevant section of the tunnel in the presence of representatives from DB AG. It was determined that the running surface of the rails was in very poor condition, so that it would not be possible to carry out the measurements. For instance, over longer sections of track and, in particular, on the curved sections in the south tube of the tunnel, serious corrugation on the rail running surface was found (see Fig. 8), as well as ‘short waves’ (see Fig. 9) (for more information on typical kinds of rail surface defects, see for instance [18]).
As was shown by measurements carried out in the section of tunnel under study in the mid-1980s, short waves of the type observed can result in an increase in the level of structure-borne noise of up to 20 dB in the frequency range of approx. 200 Hz, which is determined by wave length and train speed (see Fig. 10, taken from [19]). This increase is of approximately the same order of magnitude as the amount of structure-borne noise reduction that can be achieved by installation of the ballast mats (see [2], and Figs. 16 and 17).

Actually, an evaluation of the detected rail surface defects by the responsible department of DB AG yielded that they could not be remedied by rail grinding and that, therefore, also based on considerations of vehicle movement dynamics (vehicle/track interaction) but, in particular, with a view to reducing the structure-borne noise emissions, replacement of the rails was necessary.

**Measurement procedure**

In April 2001, following replacement of the rails, the new rails were ground as is common practice, in order to remove manufacturing defects and to create an optimal rail profile (see, for instance [18]: “preventive grinding”). After a break-in period of roughly three weeks, optimum rail running surface conditions were present for the measurements of structure-borne noise in the tunnel section under study, as was the case before and after installation of the ballast mats in 1983. In Fig. 11, the ‘smooth running surface’ of the rail can be observed (the outer edge of the rail head, outside of the rail running surface area, still shows clear traces of the grinding disk from the rail grinding train).

The locations of the measurement points set up in the north and south tubes of the tunnel are illustrated in Fig. 12. Four measurement points for each direction of travel were set up on the tunnel walls, at a height of approx. 1.5 m above top of rail, at the same locations as originally used for the measurements that were carried out before and after installation of the ballast mats in 1983.

For each direction of travel, three of the measurement points were in the area fitted with ballast mats, while one measurement point was located outside this area. Piezo-electric acceleration pick-ups were used as measurement devices, which were fitted on the existing, still intact original mounts, consisting of aluminium plates affixed with adhesives to the tunnel walls.

At first, the passages of both types of train that are operated on the Munich rapid transit system were measured, i.e. the Class ET 420 (old) and the Class ET 423 (new) multiple unit trains. However, in the further evaluations, only the results for the ET 420 multiple unit trains were used, as comparison with the earlier measurement results was only possible with this type of vehicle.
Evaluation of measurement results

Evaluation of the measurement results was carried out in an identical manner as of those obtained in 1983 (for details see [16]). Accordingly, using a special algorithm, a time frame of four seconds was established around the maximum point of the time scale of the train passage for each individual measurement and measurement point. The signals falling within this time frame were filtered using digital 1/3-octave-band filters and then, with a time constant $\tau = 1$ s (SLOW), integrated to the vibration velocity. Following this, the resulting 1/3-octave-band spectra of vibration velocity levels (so-called ‘Max-HOLD spectra’) were depicted as a function of the 1/3-octave-band centre frequency in the range 4 Hz to 315 Hz. This enabled any distorted passage of train (e.g. flat spots on the wheels) to be recognised and removed from further evaluation.

From the resulting spectra for each individual passage of train, the energetic mean value of the 1/3-octave-band spectrum of vibration velocity levels was determined for all passages of train per measurement point, and then compared with the corresponding spectra obtained from the measurements carried out immediately before and after installation of the ballast mats in 1983.

Fig. 13 shows an example of this comparison for a single measurement point outside the ballast mat area in the south tube of the tunnel during passages of rapid transit trains, Class ET 420, at a speed of 60 km/h, before and after installation of the ballast mats, type Sylomer® B 851.

![Fig. 13: 1/3-octave-band spectra of vibration velocity levels measured at the measurement point Mp7 outside the ballast mat area in the south tube of the tunnel during passages of rapid transit trains, Class ET 420, at a speed of 60 km/h, before and after installation of the ballast mats, type Sylomer® B 851.](image)

Fig. 14: 1/3-octave-band spectra of vibration velocity levels measured at measuring point Mp1 within the ballast mat area in the north tube of the tunnel during passages of rapid transit trains, Class ET 420, at a speed of 60 km/h, before and after installation of the ballast mats, type Sylomer® B 851

Fig. 15: 1/3-octave-band spectra of vibration velocity levels measured at measuring point Mp8 within the ballast mat area in the south tunnel during passages of rapid transit trains, Class ET 420, at a speed of 60 km/h, before and after installation of the ballast mats, type Sylomer® B 851.

In order to compare the long-term efficiency of the ballast mats to that measured immediately after their installation in 1983, the 1/3-octave-band level differences were determined for each measurement point, using the mean vibration velocity spectra for the situations “before installation” and “18 years after installation”, from which then the arithmetic average for the three measurement points combined, for each direction of travel (north and south tube of the tunnel), was calculated. The mean value of this 1/3-octave-band vibration velocity level difference for the situation “18 years after installation” was then depicted graphically as a function of the 1/3-octave-band centre frequency and compared to the corresponding mean value for the situation in June 1983, i.e. immediately after installation of the ballast mats. Fig. 16 and 17 show the comparison for the north and the south tube of the tunnel, respectively (in this article, the “insertion loss” of the ballast mats is not referred to, but rather the level difference, as is illustrated in Figs. 16 and 17. This is because, due to a range of practical reasons, the level difference observed at the measurement point outside the area of ballast mats is not used as a corrective factor, as was done when the insertion loss was determined at the time of installation of the ballast mats in 1983).

At first glance, the diagrams in Figs. 16 and 17 show no significant loss in efficiency of the Sylomer® B 851 ballast mats, even after 18 years of use under extremely demanding load conditions.

Regardless of the results of the following further analysis of the measurement data, it can already be observed from the diagrams presented in Fig. 14 and 15 that no significant changes have occurred compared to the state of affairs immediately after installation of the ballast mats. Consequently, the conclusion can be drawn that the efficiency of the mats is unimpaired, even after 18 years of use under extremely demanding load conditions. The expectations based on the results of the analyses conducted on the test rigs (see section "laboratory tests") have thus been fully met.

![Fig. 14: 1/3-octave-band spectra of vibration velocity levels measured at measuring point Mp1 within the ballast mat area in the north tube of the tunnel during passages of rapid transit trains, Class ET 420, at a speed of 60 km/h, before and after installation of the ballast mats, type Sylomer® B 851.](image)

![Fig. 15: 1/3-octave-band spectra of vibration velocity levels measured at measuring point Mp8 within the ballast mat area in the south tunnel during passages of rapid transit trains, Class ET 420, at a speed of 60 km/h, before and after installation of the ballast mats, type Sylomer® B 851.](image)
alone, it is more likely that due to deterioration of the ballast condition, as well as other contamination and related settling in the ballast bed, the effective loaded mat area per sleeper and, consequently, also the effective dynamic stiffness of the mats have increased (for more details on this issue, in particular the formulae for the effects described, see [6] and [7]).

In the results for the south tube of the tunnel, shown in Fig. 17, the aforementioned effects seem to be even more pronounced at first glance. But, if one takes into account that, compared to the conditions after installation of the mats in 1983, no discernible shift in the system’s resonant frequency, which is primarily determined by the unsprung wheelset mass and the (effective) dynamic stiffness of the ballast mat (see [6], [7]), has occurred, then the currently somewhat lower level difference shown in Fig. 17 for the frequency range above roughly 63 Hz cannot be attributed to a stiffening of the ballast mats. According to the usual, well-substantiated models for the description of vehicle/track interaction (see, for example, [6], [20], [21], [22]), the level reduction achieved by a ballast mat in this higher frequency range is primarily determined by the relation of the dynamic ballast stiffness to the (effective) dynamic stiffness of the mat.

Thus, if a stiffening of the ballast mat for the aforementioned reasons cannot be the reason for the slightly lower level difference vis-à-vis 1983, then the observed effect can be explained if one assumes that the stiffness of the ballast bed has decreased in the meantime.

Conclusions

The results of the tests and analysis described in this article indicate that the Sylomer® B 851 ballast mat has performed exceptionally well over a period of 18 years under extremely high operational loads of more than 760 10^6 load tons. The stringent requirements set for the reduction of structureborne noise when the mats were originally installed are still fully complied with. Even the fact that the mats were submerged in water, as was found when the samples were removed, had no detrimental impact on the efficiency of the ballast mats. These studies which, to a certain extent, can be considered as a long-term, practical test of Sylomer® ballast mats, clearly show that a long-term, very high level of efficiency can be ensured using these products. This is particularly interesting for retrofit installations of ballast mats, as is witnessed by successful projects carried out in the recent past (see [9] and [10]).

In conclusion, an evaluation is presented which, in [12], summarises the results of the tests carried out on the ballast mat samples removed: “… Based on these results, full functionality of the ballast mats can be expected for at least another 30 years, provided that the loads on the mats remain at the same level. For further clarification we recommend another removal of samples in about 10 years, or after 500 10^6 load tons, respectively.”

Plans call for complying with this recommendation by carrying out the tests described in this article again around the year 2010.

References

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