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Study on the shear strength of reused track ballast material

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ABSTRACT: A study of the shear strength of different types of railway ballast is presented. Sections of the layers of a railway track were physically modelled in the laboratory and rigorously tested under the loading conditions of rail traffic, including both fouled and clean ballast. The study not only evaluated the shear strength properties of clean and contaminated ballast, but also investigated various deformation properties such as stiffness and damping. The ballast was tested in a large-scale simple shear mode, in a device that can accommodate specimens from 40 cm x 40 cm and up to 80 cm in height. This allows the specimens to be loaded in full-scale conditions. The paper presents the test programme and loading procedures for two types of ballast specimens. Stress-strain curves are also presented as a result of the tests. A clear difference in the shear strength of clean and fouled ballast is observed, while the stiffness of both materials does not differ significantly at small strain ranges. The stiffness of the fouled material decreases more markedly as the strain range increases.

1 INTRODUCTION

The railway track is a geometrically simple structure consisting of an upper structure (rails, sleepers, and ballast) and the track foundation (sub-ballast, blanket - optional, and subgrade) built on the subsoil/natural ground. The track bed, composed of ballast and sub-ballast layers over a prepared subgrade, reduces stress on the subgrade and enhances track performance, especially ride quality.

To function effectively, the rail track must have a uniform shape and thickness longitudinally, be well-draining, prevent sleeper movement, and maintain proper track position. The cross-section shape and dimensions of the rail beam depend on track type, sleeper specifications, subgrade inclination, and track geometry. Railway track ballast, typically 22.4 mm – 63 mm in size, must be clean, cold-resistant, and dust-resistant, meeting the European standard EN 13450 for quality, extraction, investigation, grain size, and acceptance.

Traffic loads are transferred via the ballast/sub-ballast layer to the track's lower structure (sub-base layer) composed of unbound aggregates. The sub-grade layer, an embankment on natural ground, can be reinforced to enhance cost efficiency and prolong structure life. Various studies have explored the shear behavior of railway ballast:

Indraratna et al. (1988) used large-scale triaxial tests to study the stress-strain behavior and degradation of ballast under static loading, noting the limitations in representing real field conditions influenced by train speed and frequency. Anderson and Fair (2008) found that a two-layer ballast system had higher shear strength and resilient modulus than ballast alone, although permanent plastic strain increased with thicker stone layers. Huang et al. (2009) investigated the impact of contaminants on ballast strength using large direct shear tests, finding that contamination affected shear strength properties and could lead to track instability and derailments. Kharanaghi and Briaud (2020) conducted large-scale monotonic direct shear tests on crushed granite, revealing non-linear failure envelopes and variable friction and dilation angles. Delgado et al. (2021) compared slag ballast and granite ballast, finding that slag exhibited greater angularity and shear strength. Chen et al. (2021) observed that fouled ballast showed lower shear stresses and resistance than clean ballast in direct shear tests.

Ballast material testing methods, such as direct shear boxes up to 30 cm x 30 cm, reveal significant cohesion and friction angles, although conventional tests often do not meet ASTM D3080-11 standard requirements regarding the maximum grain size. Stark et al. (2014) addressed this by developing a larger shear box (0.76 m x 0.81 m x 0.50 m), which showed no cohesive shear strength and a shear angle of 51°. Estaire et al. (2017, 2018) used a 1 x 1 m shear box at the CEDEX laboratory to further test ballast. Furthermore, the CEDEX facility can also test full-scale track sections under real traffic conditions, although these tests are expensive and demanding.

This study evaluates the shear strength of track ballast through tests on clean and fouled ballast specimens. Laboratory tests used a Large-Scale Simple-Shear Apparatus (40 cm x 40 cm shear area, and 39 cm specimen height).

2 EXPERIMENTAL PROGRAM

2.1 Testing device

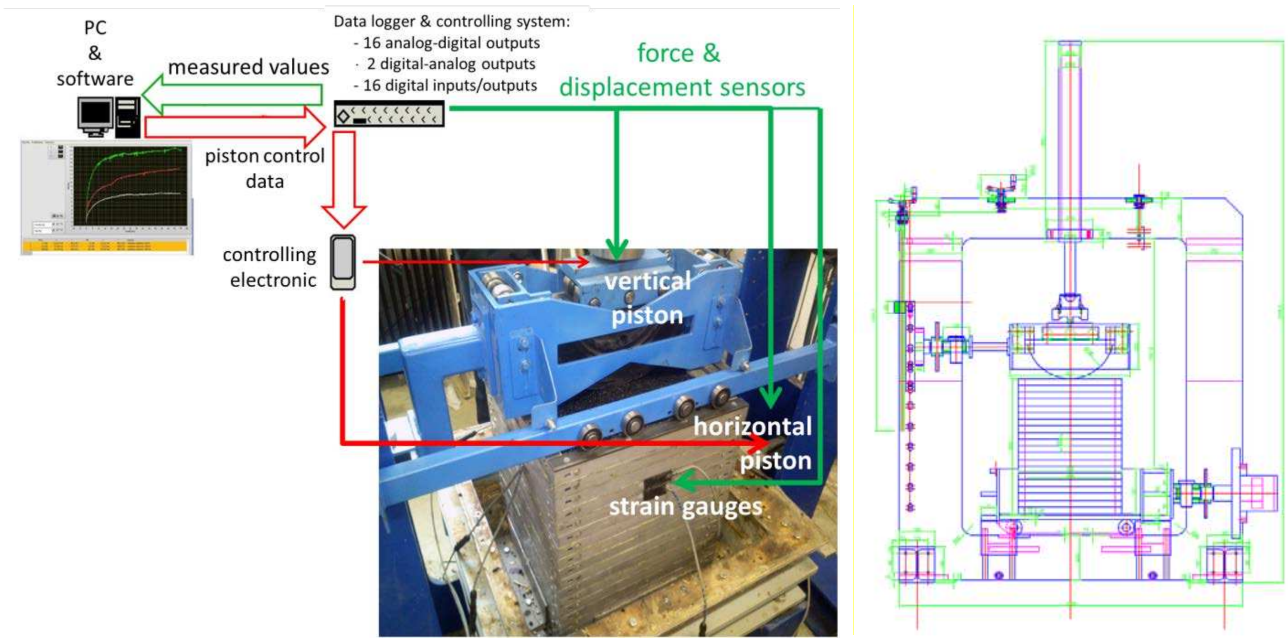
The experimental program with the laboratory tests, the materials used, and the details of the investigation are described in this section. Simple shear tests and other accompanying laboratory tests were carried out at the Slovenian National Building and Civil Engineering Institute (ZAG) in Ljubljana, Slovenia.

Large-Scale Simple-Shear Apparatus is presented at Fig. 1. Specimens were constructed within 13 rigid aluminium frames (Figures 1 and 3). Free non-frictional movements of frames were allowed in a horizontal direction without friction. The height of each aluminium frame is 3 cm and the internal layout dimensions of the frame are 40 cm x 40 cm. The loading in the vertical direction and horizontal direction was applied by hydraulic piston through the upper plate and the lower aluminium frame.

The test was carried out in three steps. Proper installation of the test specimen is the first step of the test. The second step is the application and calibration of the sensors, one of the crucial tasks to obtain high-quality results. After each test, the test specimen was removed from the apparatus's box, and it was cleaned up to install the next test specimen.

2.2 Specimen preparation

Testing of two specimens, one prepared from clean ballast and the other one from fouled ballast, is presented in this paper. Each of the specimens was embedded in a rubber membrane within the rigid aluminium frames of the large simple-shear apparatus to avoid material loss between the frames. Prismatic specimens with a cross-section of 40 cm × 40 cm and a height of 39 cm were produced by light compaction in the dry state. The weight of the specimens was measured for each individual test. Shear box with clean track ballast material is shown in Fig. 2.



a) b)

Figure 1. The laboratory test equipment: Large-Scale Simple Shear Apparatus during the test (a); Scheme of apparatus (b).

Figure 2. Shear box with clean track ballast material.

Figure 3. Large-Scale Simple Shear Apparatus at ZAG.

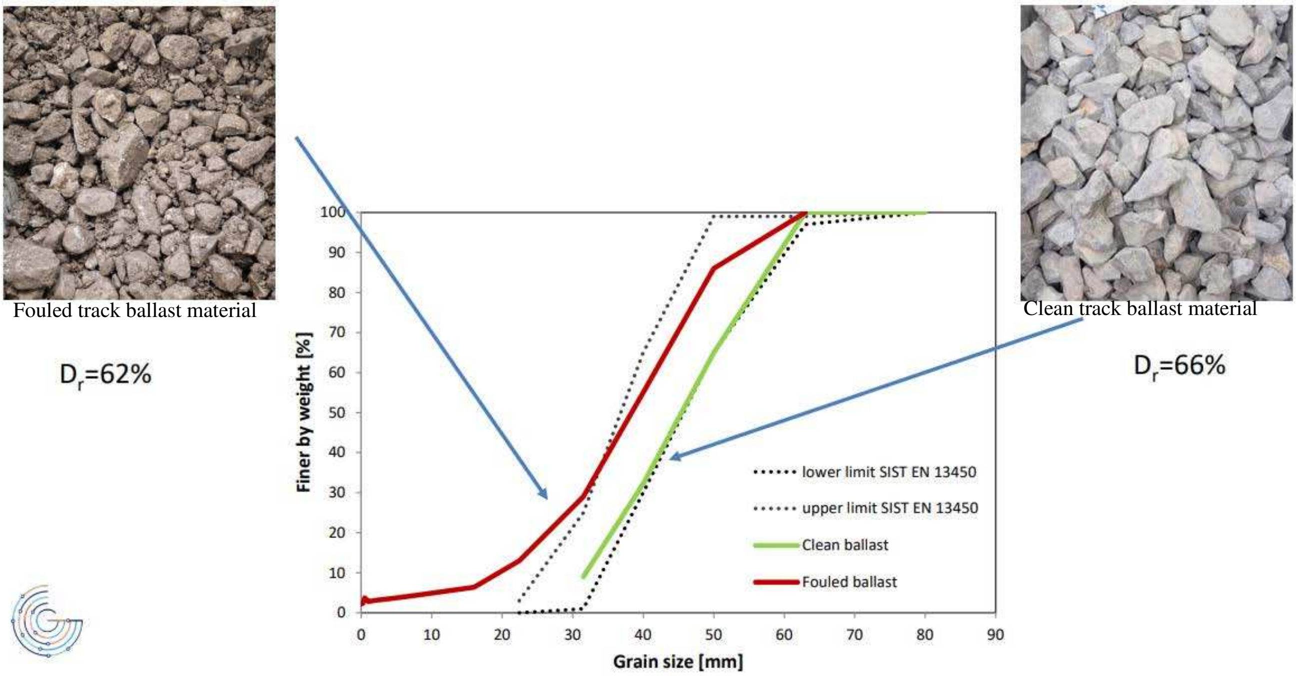


Figure 4. Grain size distribution of samples inside the upper and lower value by EN 13450.

Table 1. Densities of specimens.

	Dry density, γ_d [kg/m^3]	**Relative Density, D_r [%]**
Clean ballast	1509	62,6
Fouled ballast	1602	66,8

2.3 Material properties

An example with an old ballast material cleaned to some extent is considered in this research. Real samples of the rail track were taken during the reconstruction of the railway line (muddy sample). For the comparison, samples of the material intended for the reconstruction of the railway line (clean sample) were used. In both two cases, origin of tested ballast material is limestone, and it is considered as a relatively soft aggregate for a ballast material (LA > 30). Fouled and clean track ballast material with their sieving curves is shown in Fig. 4.

Each of the test specimens was installed in such a way as to achieve the maximum compaction found in the field. Their densities are presented in Table 1.

2.4 Loading procedure

The test begins with a careful lowering of the plate for the corresponding vertical load. Thus, selected constant vertical stress of 200 kPa is applied. After that, shear loading with a gradually increasing shear strain is then applied. Cyclic loading was similarly performed for both two specimens, each with a gradually increasing shear strain in a range between 10^{-5} and 10^{-1} mm. Details of loading procedure are shown in Table 2.

Loading is driven in strain-controlled mode. Every loading step consists of 3 load cycles, which are performed at the same displacement amplitude. Loading rates change from loading step to step and are defined in the way that every load cycles last 3 minutes.

Table 2. Cyclic loading procedure.

step No.		**DISPLACEMENT AMPLITUDE**	**loading rate**
(3 cycles)	**γ [%]**	**s [mm]**	**[mm/min]**
1	**0,0010%**	**0,00187**	0,0075
2	**0,0020%**	**0,00374**	0,0150
3	**0,0040%**	**0,00748**	0,0299
4	**0,0080%**	**0,01496**	0,0598
5	**0,0160%**	**0,02992**	0,1197
6	**0,0320%**	**0,05984**	0,2394
7	**0,0640%**	**0,11968**	0,4787
8	**0,1280%**	**0,23936**	0,9574
9	**0,2560%**	**0,47872**	1,9149
10	**0,5120%**	**0,95744**	3,8298
11	**1,0240%**	**1,91488**	7,6595
12	**2,0480%**	**3,82976**	15,3190
13	**4,0960%**	**7,65952**	30,6381
14	**8,1920%**	**15,31904**	61,2762

Strain measurement data was collected from seven LVDT sensors attached to the upper plate and frames of the device. Four of them measured vertical displacement, one measured horizontal displacement in large strain range, while two of them were devoted to measure displacements in small strain range.

The measurements of the LVDT sensors were recorded using adequate software connected to the device. After lowering the plate for the vertical load and consolidation settlements, the horizontal load is applied. The software provides a correlation between the force load and the strains so that a cyclic load is recorded. The software outputs tables with values for time, loads, and displacements. These values are used to create graphs to determine the deformation characteristics.

Figure 5. Deformed test specimen on the Large-Scale Triaxial test apparatus.

3 TEST RESULTS AND MODELING

The investigation of the deformation properties of the railway track ballast is presented to determine the influence of fouling of the railway ballast on the changes of its deformation properties, such as stiffness and damping.

Fig 6 and 7 presents typical hysteresis loops for clean and fouled ballast. One can observe that the hysteresis loops are pretty much similar and thus the damping characteristics of both types of material does not differ much. On the other hand, stiffness already at small strain range is lower for fouled ballast when compared to the clean one (see detailed figure for small strain range at Figure 6 and 7).

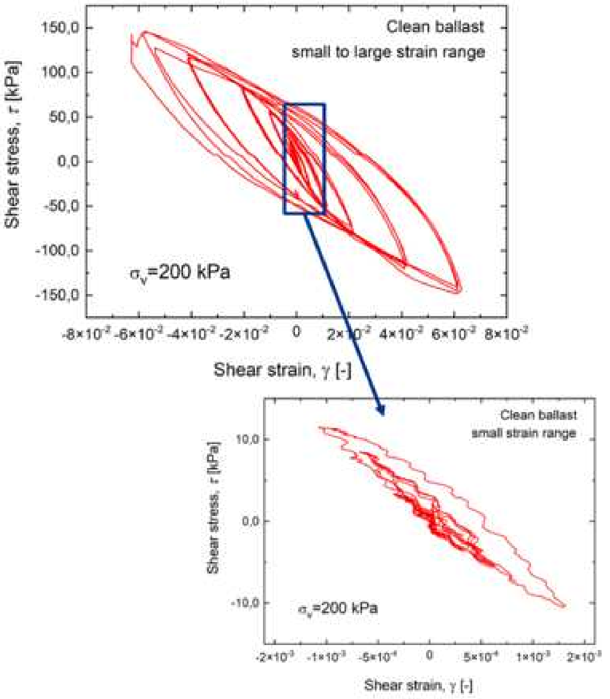


Figure 6. Clean track ballast material

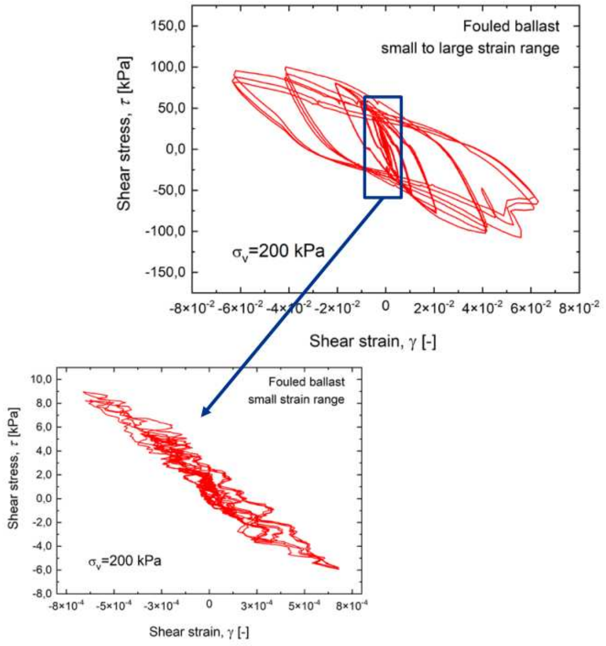


Figure 7. Fouled track ballast material.

However, changes between fouled and clean material become more prominent with an increase of strain range. One can observe from Figure 6 and 7 that shear stress causing nearly the same strain in the case of clean ballast is almost 50% higher (approximately 150 kPa) than in the case of fouled material (approximately 100 kPa). Similarly, the stiffness degradation curves presented at Figure 8 for both materials show more significant degradation for fouled ballast compared to clean one. Results from deformation properties characterization tests of ballast material conducted by other researchers (Dyvik and Kaynia, 2018) are shown for comparison. It should be noted that the later tests were conducted in triaxial testing mode and that the tested material was of harder type of stones, while material used in the presented research was more degradable limestone.

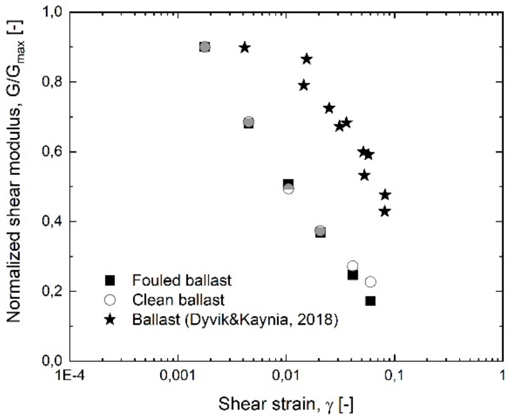


Figure 8. Stiffness degradation with an increase of strain

4 CONCLUSIONS

When reconstructing old railroad lines, ballast must be removed, which is considered waste. Large quantities of the excavated material can be reused for the new track substructure. Railway track ballast is a frost- and water-resistant stone material with angular grains of different sizes, whereby the grain size can be the same when removing an old railway track or can be defined by reuse methods. The resilience of a railway track refers to its ability to absorb and dissipate the dynamic loads generated by passing trains and to return to its original shape and position after deformation. It depends on several factors, including the design and construction of the track, the type and condition of the rail and ballast, and the properties of the underlying soil or rock.

A study was conducted to evaluate the deformation properties of track ballast material evaluated by testing different types, i.e. clean and fouled track ballast specimens. Large scale simple shear tests were performed at specimens 40 cm × 40 cm in area and 39 cm in height. Such a size of a specimen fulfils the requirements regarding the maximum grain size according to the ASTM D3080-11.

Before performing the tests, the geometrical and physical properties of both ballasts were obtained according to EN-13450.

The following conclusions were obtained from the study:

- The use of large scale simple shear device of size 40 cm × 40 cm × 39 cm heigh made it possible to analyze the deformation properties of ballast material.
- The hysteresis behaviour of fouled and clean ballast seems quite like each other.
- Stiffness of fouled ballast is considerably lower compared to the stiffness of clean ballast and it also decreases more with an increase of strain range.
- Stiffness degradation of ballast material observed within this research is higher compared to other published results, with taking a note that other published research has been performed with harder ballast material and in triaxial testing mode.

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