EPJ Web of Conferences **340**, 07017 (2025) https://doi.org/10.1051/epjconf/202534007017
Powders & Grains 2025

Comparison of the compression and shear behavior of clean and fouled ballast

Claire Silvani[1,*] and *Irini* Djeran-Maigre[1]

[1]Univ Lyon, INSA Lyon, GEOMAS, 69621 Villeurbanne, France

Abstract. The railways are still a highly demanded mean of transportation worldwide, thanks to their cost efficiency, ease of drainage, and capacity to withstand cyclic imposed loadings from trains. The track structures, composed of ballast, frequently undergo deformations of high levels so that the new ballast is progressively degraded and the generated fouling material between ballast particles could cause rail track defects. This paper investigates the influence of fines on the strength properties and deformation characteristics of ballast fouled with two kinds of fines: a fouling made by stone dust of the same parent rock (limestone in our case) and a clay-based fouling with two kinds of tests: oedometric compression and direct shear tests. In the oedometric tests, the ballast fouled with the clay particles results in the reduction of compression strength properties while the natural fouling strengthens the sample. Reduction in the friction angle of the granular assembly with fines is globally measured in both cases, inducing a decrease in the load-bearing capacity of the material. Depending on the loading type, the results don't show the same tendency for each type of fouling.

1 Introduction

The railways are still an efficient and economical mean of transportation throughout the world, thanks to their cost efficiency, ease of drainage, and capacity to withstand cyclic imposed loadings from trains. This trend is likely to continue to grow as carbon emissions are reduced and the goal of a more energy-efficient society is pursued. The granular layer that forms part of the railway tracks generally consist of an upper ballast layer composed of large and angular particles (typically 20 - 60 mm) and a lower layer of capping material resembling road base. The main functions of the ballast layer are to control the stress intensity projected onto the weaker subgrade, to decrease the frequency of track maintenance by minimising track settlement and sleeper movement, and to promote rapid drainage via the large pore structure [1].

The track structures, composed of ballast, undergo high levels of vertical stress due to load-unloading cycles with increased traffic densities so that the new ballast is progressively degraded and the generated fouling material between ballast particles could cause rail track defects, such as differential settlement, impeded drainage and reduced bearing capacity [2]. This may be due to the increase in the number of fine particles, which widens the particle size distribution.

Ballast fouling materials have also other sources such as fouling attributed to the dust from trains carrying coal or soil intrusions from the base [3] or to particles coming from windblown processes. When fouling becomes important, ballast life expires and should be cleaned or replaced.

Degradation of ballast is a main issue for railway owners and thus studied by many researchers [1-7]. Many studies have been carried out on ballast strength and on degraded ballast with fouling produced by ballast inherent degradation, but fewer studies have been carried on the behavior on ballast contaminated by soil intrusions like plastic fines coming from the bottom of the track.

Ballast health can be estimated with its breakage ratio. Several criteria have been expressed in the literature to quantify the breakage in granular media. All of the breakage indexes (Br) compare the difference of the initial grading to the final one (usually called Bt) to an area defined between the initial grading to an ultimate grading (called Bp). It is in the definition of the ultimate particle size distribution, defining the breakage potential Bp, that the criteria proposed in the literature differ.

Einav [8] proposed an ultimate grading based on a fractal law, with parameters depending on the material (maximum diameter and type of granular material). This criterion is one of the last most used proposed in the literature. The former criteria proposed a breakage potential defined by a unique upper boundary for all kinds of soils. One of the well-known is Hardin's [9]. He defined the upper limit of breakage, assuming that it was possible for all particle sizes to be reduced to silt-sized particles at high pressures. Its upper limit is defined by dmin=0,074 mm, making a high Bp. Indraratna *et al.* [1] changed also the ultimate curve, but on both boundaries, extending from d95 of the maximum sieve aperture dmax to the smallest sieve aperture dmin (equal to 2,36 mm in this case). Finally, improvements in Br by Indraratna and Einav have led to a decrease of Bp compared to Hardin [9] (Bt is kept the same for all the definitions).

Several authors have studied the shear strength properties of fouled materials [4-7]. Several types of shear tests have been performed (direct shear and triaxial tests) on fouled ballast contaminated by different agents, wet in most experiments (such as plastic soil fines, mineral filler).

The conclusions are clear for the addition of plastic fines: they reduce ballast strength for both direct shear

---

* Corresponding author: claire.silvani@insa-lyon.fr

and triaxial tests [4,7], while the addition of fines from the abrasion of the parent rock seems to increase its strenght in triaxial tests for Qian et al. [5] but not in the direct shear tests of Huang et al. [7].

The experiments proposed here seek to quantify the deformation and fracture potential of different fouled granular media: fouled ballast is tested with different types of fines (clay type fines or fines from the degradation of the parent rock) to simulate two types of pollution with different percentages. Two types of experiments have been conducted to answer this question: large oedometric and direct shear tests, according the apparatus available in our laboratory.

2 Experiments and methods

2.1 Materials

Clean ballast of limestone and contaminated ballast with fines are tested under oedometric compression and using a large direct shear box. The grains' size of the reference material (clean ballast) ranges between 10 and 40 mm.

The samples of fouled ballast have been generated by adding fine particles to the clean ballast granulometry. A fouling made by stone dust of the same parent rock (limestone in our case) and a clay-based fouling made of kaolinite particles are studied. Several fouling indexes are tested per each type of fines. The degraded ballast is represented by sample including fines of grain size d less than 10 mm while plastic fines have a medium particle size between 1 and 20 µm Ballast and fines are mixed by hands and layer by layer taking care to blend the surfaces to ensure a homogeneous sample. The typical granulometries of the different materials can be seen on Figure 1.

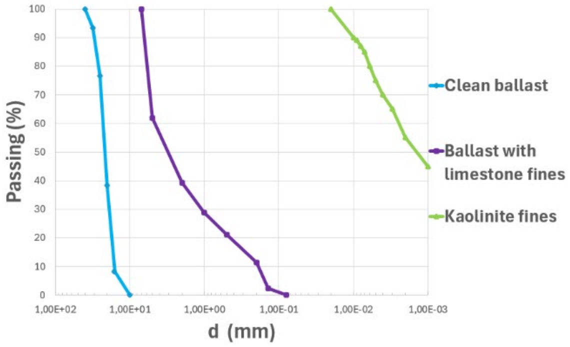


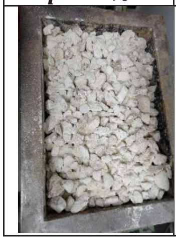
Fig. 1. Typical granulometries of clean ballast, degraded ballast (with limestone fines), and kaolinite particle size distribution.

An overview of the different tests is proposed in Table 1 (with 2 different fouling indexes tested for limestone fines, versus 3 for kaolinite fines). The % of fouling p is defined as the ratio of the mass of fines (d<10 mm) over the total mass of the soil. The weight of the initial (clean) mixture is kept constant for each test and fouling is added to this mass.

2.2 Devices

Large size cells are used to perform the tests and are presented in Fig. 2. An acceptable ratio (between 1/5 and 1/7) between the maximum grain size to the dimension of the apparatus is respected (all the more so as the percentage of larger particles is low).

Table 1. Photos of the materials used with their different fouling percentages p

Clean ballast $p = 0\%$	**Ballast with limestone fines** $p = 18\%$	**Ballast with limestone fines** $p = 31\%$
		
Ballast with plastic fines $p = 5\%$	**Ballast with plastic fines** $p = 10\%$	**Ballast with plastic fines** $p = 18\%$
		

The vertical stresses can reach more than 2.5 MPa for the oedometric tests while the maximum normal stress applied is 85 kPa for the direct shear box (limitation given by the apparatus used).

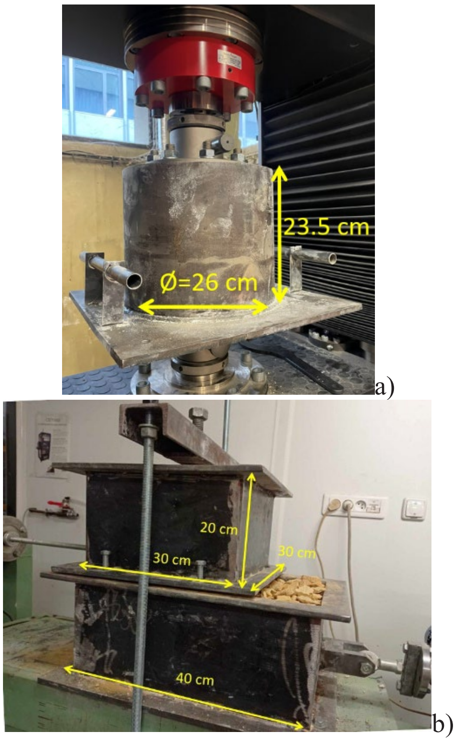


Fig. 2. a) Oedometric cell and b) direct shear box with a square shearing surface.

3 Results

3.1 1D compression tests

The stress-strain curves obtained for clean and degraded ballast are presented in Figure 3. Several tests have been performed for each type of parameter (between 2 and 5) to evaluate the repeatability. Repeatability is not obvious, especially for clean ballast where the results seem to depend on the initial grain arrangement. The median curve for each parameter is selected to avoid overloaded graphics (except for limestone fines with p=31% where only two tests have been performed). Two different behaviours can be revealed when comparing the two types of fines. The introduction of limestone fines to limestone matrix induces less strain for the same stress level, thus improving the mechanical properties of the sample. The greater the mass of fines, the more the sample is stiffened. The tests with kaolinite fines don't show the same effect: the sample deforms more when the proportion of fines is increased. An increasing mass of clay particles seems to act as a lubricant permitting the rearrangement of grains, probably due to the loss of contacts between large particles. The friction coefficient between both types of fines and matrix seems to play a dominant role in the compaction behavior of the samples.

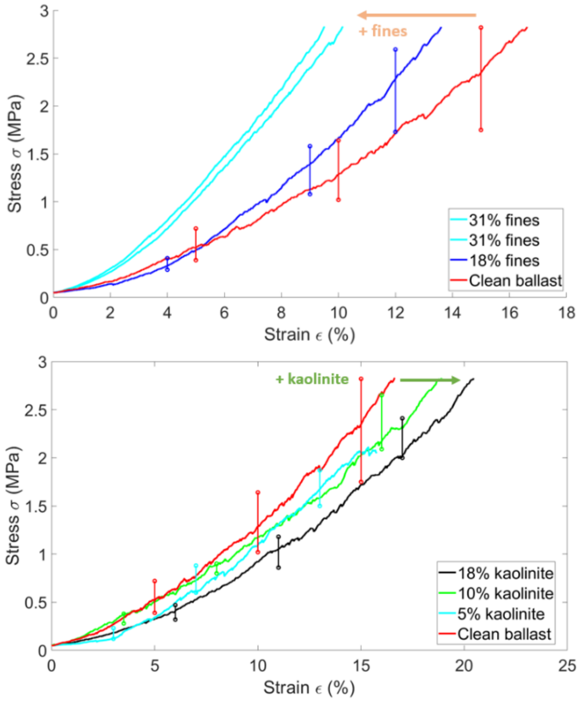


Fig. 3. Stress-strain curves (with errors bars) for oedometric tests for limestone fines (above) and kaolinite fines (below).

The breakage behavior of this mixture has also been studied. Einav [8] and Indraratna's [1] ultimate criteria for large grain sizes are below the final (and even initial) particle size curves chosen, leading to a negative Bp calculation. To avoid this pitfall, Hardin's criterion will be used, not focusing on the value of the breakage rate but considering the variation in this rate of mixes with fines compared to the clean mix. Moreover, a minimum sieve of 10 mm is chosen (instead of 0.074 mm in Hardin's criterion) to calculate Bp to emphasize on breakage on large grains.

It should be noted that with the Hardin's criterion, Bp is higher than with the other criteria, so the Br obtained are smaller than those that should have been obtained with the other criteria, but our comparison will be relative to the material without fines.

Figure 4 shows the different breaking ratios. The presence of limestone pollution has a positive effect on breakage. Br seems to diminish with fouling. The decrease of grain breakages could be explained by the homogenization of the force distribution around large particles due to the presence of small particles surrounding them. Increasing the number of contact points reduces the potential rupture.

There's no clear evolution with kaolinite fines. At the end of the oedometric tests, it should be noted that the kaolinite remained stuck to the limestone grains, thus accounting for the mass of the limestone grains and distorting the balance. In an attempt to correct this, the "lost" kaolinite mass is removed in proportion to the measured limestone masses for each sieve size. This improvement in the way masses is taken into account still doesn't give clear results, but shows a breakage rate that seems to increase with the presence of fines. This is not in line with the results of [4], which calculated the failure rate of ballast fouled with kaolinite clay, but based on triaxial tests with wet clay so that the comparison can't be straightforward.

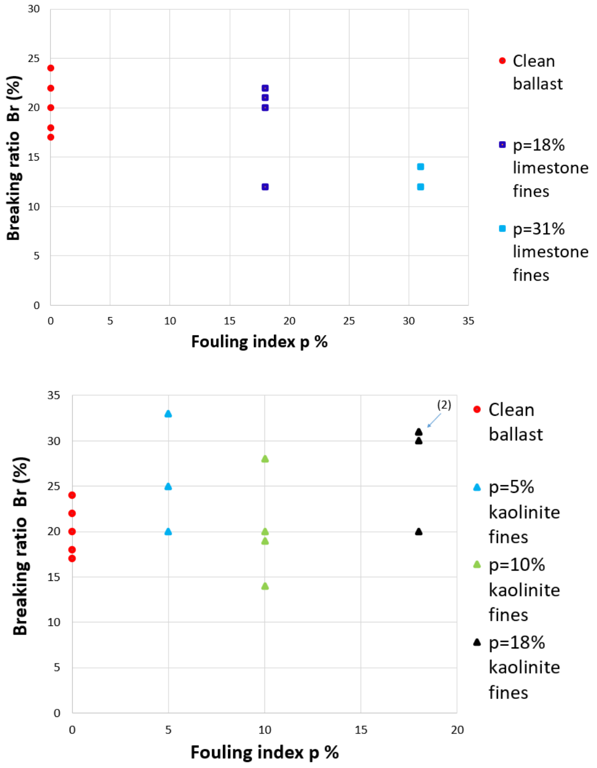


Fig. 4. Breaking ratio for the different mixtures with limestone fines (above) and kaolinite fines (below) calculated with Hardin criterion, with a minimum sieve diameter equal to 10mm for the calculation of the breaking potential Bp.

3.2 Direct shear tests

A minimum of three tests are done for each mixture (with different normal stresses) so that the friction angle can be deduced. The friction angles obtained are presented on Table 2. The addition of natural fines (a) results in a lower angle of friction, which tends to decrease with increasing fines. This tendency is also observed in [7]. One hypothesis to explain this is that the fine particles position themselves around the grains, allowing them to slide easily between them. One can also imagine that at p=18% mass percentage, there is still a rock matrix, whereas at 31%, there is an earth matrix. Earth-type materials do indeed have a lower angle of friction, and a higher cohesion than coarse granular materials.

Regarding plastic fines, the addition of clay leads also to a lower angle of friction (Table 2b), but more or less significantly, not directly proportional to fouling. The same tendency is also observed in [7] while the normal stresses applied are higher. One hypothesis to explain this behavior is as follows: when there is little clay, it lightly coats the limestone grains and causes them to slide between each other, while still having sufficient void volume to slide. When more clay is present, it occupies virtually all the voids, preventing the limestone grains from sliding.

Table 2. Friction angles for a) limestone fines and b) kaolinite fines for different percentages of fouling.

a)	Fouling index p		
Limestone fines	Clean ballast p=0%	p=18%	p=31%
Friction angle Ø (°)	45	45	32

b)	Fouling index p			
Kaolinite fines	Clean ballast p=0%	p=5%	p=10%	p=18%
Friction angle Ø (°)	45	30	40	41

4 Conclusions

The tests measured strength and deformation characteristics of both clean and fouled ballast aggregates with two different fouling agents (a natural fouling and a plastic fouling) in two types of experiments: 1D compression and shear tests. The oedometric tests showed that ballast fouled with the clay particles results in the reduction of strength properties compared to the natural fouling that has strengthened the sample. The final particle sizes have been studied in the light of the breaking ratios. Calculation of the breaking ratios is related to three granulometries: initial, final and ultimate. The shapes of the initial granulometry and the obtained final granulometry do not allow us to use the ultimate fractal curve proposed by certain authors in the literature. This difficulty can be overcome by using Hardin's criterion. A reduction in the breaking values is noticed as a function of the percentage of fouling for natural fouling, whereas for clay fouling a high dispersion is observed and the results not easy to treat, as kaolinite is stuck to the ballast grains. As the literature is poor concerning the calculation of breaking ratios (probably due to the long times and thoroughness of the sieving tests with a high volume of material), the comparison with other tests is not straightforward, as several parameters are different. Finally, shear tests with a shear box are performed and the addition of fines leads globally to a lower angle of friction in both cases, but more or less significantly with the plastic fines. Depending on the loading type, the presence of fines doesn't lead to the same tendency especially for the natural fouling where the samples are strengthened under oedometric compression while the load-bearing capacity of the material seems to be decreased owing to the reduction in the friction angle. This has to be clarified: although a reduction in friction angle is noted, the shear stress vs. normal stress curves don't show a clear differentiation on the influence of clean or fouled ballast between each other. It should also be noted that the level of applied stresses is not the same in both cases.

Acknowledgements to INSA's students who worked with us: B. Pecusseau, R.Dutarte, E.Valles-Lopez and other students from CESI.

References

1. B. Indraratna, J. Lackenby, D. Christie. Effect of confining pressure on the degradation of ballast under cyclic loading. Geot., **55**(4), 325-328 (2005).
2. B. Indraratna, W. Salim, C. Rujikiatkamjorn: Advanced Rail Geotechnology - Ballasted Track. Routledge, Taylor & Francis Ltd (2011).
3. P. Anbazhagan, S. Lijun, I. Buddhima, R. Cholachat, Model track studies on fouled ballast using ground penetrating radar and multichannel analysis of surface wave. J. App. Geo., **74**(4) 175-184 (2011).
4. B. Indraratna, N. C.Tennakoon, Nimbalkar, S. Shrawan, C. Rujikiatkamjorn. Behaviour of clay fouled ballast under drained triaxial testing. Geot., **63**(5), 410-419 (2013).
5. Y. Qian, E. Tutumluer, Y. M. Hashash, J. Ghaboussi, Triaxial testing of new and degraded ballast under dry and wet conditions. Trans. Geot., **34**, 100744 (2022).
6. A. K. Rohrman, C. L. Ho, Effects of fouling containing plastic fines on abraded ballast strength and deformation properties. Trans. Geot., **21**, 100278 (2019).
7. H. Huang, E. Tutumluer, W. Dombrow, Laboratory Characterization of Fouled Railroad Ballast Behavior. Transp. Res. Rec., 2117**(1)**, 93-101 (2009).
8. I. Einav, Breakage mechanics—part I: theory. J. Mec. and Phys. of Sol., **55**(6), 1274-1297 (2007).
9. B. O. Hardin, Crushing of soil particles. J. Geot. Eng., **111**(10), 1177-1192 (1985).