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Experimental investigation of mixing railway ballast grains with different form - Part II: Mechanical characterisation using large-scale direct shear tests --Manuscript Draft--

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Abstract:	The paper investigates the effect of grain form on the mechanical behaviour of railway ballast aggregates using large-scale shear box tests. Three types of Hungarian andesite railway ballast assemblies were tested: a compact, a non-compact and a mixed one (23 mass% non-compact). The mixed assembly had the highest internal friction angle (77.6°) for the maximum shear stress values, while the internal friction angles were 72.0° for the non-compact and 69.9° for the compact assembly. The amount of broken mass and the failure modes of the grains were also recorded. It was found that the non-compact assembly had the highest amount of broken mass. A novel method was used to calculate the displacement field of the grains: it was computed from the scratches on the shear cell walls, using image processing, which proved to be applicable and in line with the numerical results published in the literature.
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Opposed Reviewers:	

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:



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Experimental investigation of mixing railway ballast grains with different form - Part II: Mechanical characterisation using large-scale direct shear tests

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Dear Editor,

My co-authors and I wish to submit the attached manuscript “Experimental investigation of mixing railway ballast grains with different form - Part II: Mechanical characterisation using large-scale direct shear tests” for publication in Transportation Geotechnics. This manuscript is the second part of two companion papers. The first part (“Experimental investigation of mixing railway ballast grains with different form - Part I: Size and form characterisation”) is submitted simultaneously with Part II. We have decided to split the topic into two companion papers, because of the amount of information they contain, and because they discuss different, but interconnected topics (geometry and mechanical characterisation of the same aggregate) and have standalone conclusions.

The two-part study focuses on a key issue of how the existence of compact and non-compact grains influence the strength of railway ballast assemblies. The novelty of the paper is that it experimentally investigates aggregates with controlled size and form content using a large-scale shear box. Moreover, it introduces shape heterogeneity by testing a compact, a non-compact and a mixed assembly with known grain-type proportions.

Part II discusses the shear behaviour of the three types of assemblies and comes to a conclusion that the mixed assembly had the highest resistance against shear. It also contains the percentage of broken mass and introduces a novel method to compute the overall displacement field of the grains from the scratches they left on the walls of the shear cell using image analysis.

The paper is an original manuscript. It has not been submitted for publication anywhere else, neither in whole nor in part. The paper is co-authored by Bence Szabó, Dr. Zsolt Farkas and Dr. Kornél Tamás who have approved the final manuscript.

Yours sincerely,

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Experimental investigation of mixing railway ballast grains with different form - Part II: Mechanical characterisation using large-scale direct shear tests

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Abstract

The paper investigates the effect of grain form on the mechanical behaviour of railway ballast aggregates using large-scale shear box tests. Three types of Hungarian andesite railway ballast assemblies were tested: a compact, a non-compact and a mixed one (23 mass% non-compact). The mixed assembly had the highest internal friction angle (77.6°) for the maximum shear stress values, while the internal friction angles were 72.0° for the non-compact and 69.9° for the compact assembly. The amount of broken mass and the failure modes of the grains were also recorded. It was found that the non-compact assembly had the highest amount of broken mass. A novel method was used to calculate the displacement field of the grains: it was computed from the scratches on the shear cell walls, using image processing, which proved to be applicable and in line with the numerical results published in the literature.

Keywords: Railway ballast; Large-scale shear box; Particle form; Grain breakage; Image analysis

1. Introduction

The mechanical behaviour of railway ballast aggregates, amongst other parameters, depends on the size and shape of the grains that make up the assembly. The roughest level of shape parameters of a grain is its overall *form* on which the present study focuses. Several experimental and numerical studies prove that non-compact grains tend to break more easily [1–5]. The majority of the numerical studies apply the discrete element method (DEM) [6]. This technique models materials with distinct elements with independent degrees of freedom. Interaction forces can rise and disappear between these elements [7]. Shi et al. [8] investigated numerically particle breakage during tamping, which is an aggressive intervention [9], and proposed that the ratio of flat and elongated grains should be limited to 20% in the ballast aggregate. In the European standard EN 13450 [10], the maximum mass proportion of non-compact grains is 30% if they are sorted with bar sieves and 35% if they are sorted using a shape index gauge [11]. According to Deiros Quintanilla, “too flat” and “too elongated” particles should not be present in ballasted tracks at all to perform its functions [12].

However, there is an opposing effect: a plethora of studies prove that the deviation from compact form increases the shear strength of granular assemblies due to increased interlocking. M.-j. Ying et al. [13] performed experimental shear box tests on geogrid-reinforced aggregates with different overall regularity and experienced that more irregular assemblies have higher shear strength. They did not investigate the effect of mixing grains with different form. Most of the shape-effect studies are numerical investigations because it is much easier to control and characterise the form of the grains in simulations than in experiments. Liu et al. [14] reported 2D DEM direct shear simulation test results, where a

decrease of sphericity [15] (i.e. deviation from a sphere in 3D and from a circle in 2D, in the latter case it is also referred as *circularity*) increases the internal friction angle of the assembly. This behaviour has also been reproduced by Talafha and Oldal [16]. Zhao et al. [17] performed DEM simulations of triaxial tests and compared the shear behaviour of monodisperse spherical, polydisperse spherical and non-spherical assemblies. Their results show that the shear strength of non-spherical assemblies is substantially greater due to interlocking effects. It was also observed that the effect of size polydispersity was limited. Linero-Molina et al. [18] claim that grain form distribution has higher order factor in shear strength than the PSD. Contrarily, the industrial practice is different: the PSD has the primary role in aggregate characterisation and form is secondary. Usually, the aggregate is graded based on particle size, then samples are taken, and particle forms are only characterised as a quality measure.

Although DEM simulations offer a precise control over particle form and let insight to the micromechanical behaviour of granular aggregates, they still have to be calibrated and verified against experimental evidence. Full-scale tests are possible [19], however the three most widespread types of experiment to calibrate the parameters of DEM models in ascending precision order are *angle of repose*, *laboratory direct shear* and *triaxial shear tests*. Higher precision comes with a price: more accurate devices are more complex. This is even more significant when the grain sizes are large and unique large-scale instruments have to be custom-made. The angle of repose test is the least accurate, as a proven, direct link between the angle of repose and the internal friction angle of granular materials does not currently exist [20]. For example, some of these uncertainties entail that the repose angle is dependent on how the heap is formed [21] or how the angle is measured [22]. Suhr et al. reported that the same angle of repose can be reproduced by a wide range parameter values for the same simulation (i.e. the *parameter ambiguity* is high) [23]. The direct shear test has a drawback as

well, as the position of the shear band is prescribed by the geometry of the apparatus, which might not be the weakest plane of the assembly. Furthermore, the theoretical stress and strain field of the grains (a horizontal shear plane is formed where the two halves of the shear cell meet) is far from reality [24,25]. Despite their disadvantages, laboratory direct shear tests are widely used, because they offer a good compromise between accuracy and complexity.

The two opposing effects (grain breakage and resistance against shear) suggest that there is an optimal form distribution. In other words, if we use industrial methods for classification, there is an optimal non-compact to compact grain ratio. This content is expected to be dependent on the material of the assembly and on the magnitude and mode of the load that it has to bear, because the interlocking effect may dominate at lower and grain breakage at higher stresses. This study focuses on the low load region, where the breakage rate is also low, and the interlocking effect dominates.

The majority of studies in the literature on the experimental testing of rock aggregates employ a large-scale direct shear test. Coetzee [26] performed direct shear tests on a crushed rock aggregate using a cylindrical (Jenike) shear cell with the purpose of using the measurements to calibrate a DEM model. The internal friction angle of the assembly calculated from measurements varied between 50.1° and 56.3° with an average of 52.8° . The aim of Suhr et al. [27] was also to calibrate a DEM model. Calcite from Croatia and Helvetic Silecious Limestone (i.e. “Kieselkalk”) from Switzerland aggregates were sheared in a box. The secant friction angles of the aggregates were between: 53.5 - 64.6° . Linero-Molina et al. performed experiments to investigate the correlation between size and form in mine waste [18] using a large-scale shear box [25]. They recorded internal friction angles between 34° and 40° . They also highlighted the influence of gap size (i.e. the distance between the two halves of the cell) on the resistance against shear. Huang and Tutumluer [28] investigated the effect of fouling on a standard railway ballast material. The internal friction angle was 31° for

the clean and 27° for the fouled assembly. Fischer and Horvát [29,30] investigated the effect of installing a geogrid [31] within a 1x1x1 m shear box. However, this device was not designed to bear high normal pressures, so the only load in their tests was gravity. Indraratna et al. studied both the effect of installing geogrids and fouling [32,33] and the internal friction angle in their tests was between 48 and 65°. Tanghetti et al. [34] designed a 1500x1500x1500 mm shear box. Li et al. [35] applied a circular shear box (504.6 mm diameter and 400 mm high plus a 15 mm shear seam) for soil-rock mixtures assemblies treated by different scaling methods and got friction angles between 17° and 35°. Further details of the reviewed direct shear experiments can be seen in Table 1.

Table 1. Details of a few large-scale shear boxes from the literature.

Publication	Device parameters			Experiment parameters		
	Cell sizes (bottom + top half) [mm]	Max. normal stress [kPa]	Max. shear disp. [mm]	Shear velocity [mm/min]	Max. grain size [mm]	Normal stresses [kPa]
Indraratna et al. [32]	300x300x92.5 + 300x300x92.5	N/A	37	2.5	40	15, 21, 51, 75
Suhr et. al [27]	300x300x100 + 300x300x100	556*	40	1	40	111, 222, 333
Huang and Tutumluer [28]	407x305x152 + 305x305x53	537*	102	12	70	172, 241, 310
Coetzee [26]	Ø590x165 + Ø590x165	183*	70	60	40	10.5, 24.0, 38.3, 52.4
Linero-Molina et al. [18,25]	720x720x250 + 720x720x350	4000	150	N/A	100	500, 1000, 2000, 3000
Horvát et al. [30]	ten segments, each segment is 1000x1000x100	N/A	55	N/A	62.5	0
Tanghetti et al. [34]**	1500x1500x750 + 1500x1500x750	622	400	N/A	100	N/A
Li et al. [35]	Ø504.6x200 + Ø504.6x200	N/A	100	N/A	80	200, 400, 600, 800

*Calculated from the limit of the vertical force sensor which is 50 kN in each case. It is advised to apply only about the 80% of the maximum force to ensure the safety of the cell.

**Design plan

The main aim of this study is to contribute towards finding the optimal ratio of compact and non-compact grains by experimentally investigating Hungarian andesite railway ballast aggregates, using a custom-built large-scale shear box. A novelty of this study is that standard railway ballast aggregate here is sorted based not only on the size of the grains but on their form as well as was described in the Part I of the companion papers. Then, assemblies (a compact, a non-compact and a mixed one) are composed with specified size and form content, then and they are sheared. A further aim is to provide data for calibration of DEM models, which can extend and refine the experimental results.

2. Materials and methods

2.1 Large-scale shear box apparatus

A unique laboratory large-scale shear box apparatus (Fig. 1 and 2) was built in the Laboratory of Building Materials and Building Physics at Széchenyi István University of Győr, Hungary, as part of this study. The shear cell was uniquely designed and manufactured for this study by welding 30 mm thick steel sheets. According to ASTM D3080 [36], the minimum width of the shear cell is 10 times and its minimum height is 6 times the size of the largest grain in the tested assembly. Because the sieve size of the largest grain is 50 mm, the inner dimensions of the cell were chosen to be 500 x 500 x 300 mm. The cell was placed on a set of rollers and the modular frame was adjusted to accommodate it. The normal and shear forces were exerted with a custom, manual and analog hydraulic system with two independent circuits. The magnitude of the normal force was adjusted with a pressure control valve and the shear velocity of the lower half of the cell was regulated with a manually adjusted aperture. During the design phase of the shear box apparatus, the aim was to keep shear velocity under 1 mm/s in all circumstances. This aim was fulfilled, with shear velocity varying between 0.1

and 1 mm/s (excluding one case, when it jumped to 1.4 mm/s for a short amount of time) with an average value of 0.33 mm/s. The measured strength of the aggregate is dependent on the freedom of the upper half and the size of the gap between the two halves [25]. During the first few initial tests, the upper half was only fixed horizontally. When the aggregate started to dilate after a short compression phase, the upper half was lifted by the forces and a gap was created between the two halves. The gap grew without limits, and the ballast assembly could not be sheared all the way till failure. Two vertical retainer bars were installed to prevent the unlimited growth of the gap, which maximised its size in 3 mm. This maximum gap was reached shortly after the dilation phase started and remained constant thereafter. A definite shear failure occurred in all tests as the result of the modification.

The shear force was measured with a 200 kN (type: MOM-Kaliber 7924, S/N 791274), and the normal force was recorded with a 50 kN (type: MOM-Kaliber, 7924 S/N 781222) force sensor. Because of the gap between the two halves, friction between the shear box parts occurred only at the rollers under the shear cell (excluding the short compression phase, where the friction between the two shear box halves was neglected). This friction was measured in separate tests and was taken into account during the computation of the shear forces. Furthermore, the weight of the upper half was added to the normal force. The normal displacement of the lid was measured with four HBM W20TK (S/N 6950, 6951, 5451 and 5013) inductive displacement sensors. Because of this, not only the average normal displacement, but also the angle of the lid could be computed (three of the four sensors were chosen in each test based on the quality of the position data they provided, and a plane was fitted to calculate the angles of inclination with the horizontal plane). The shear displacement was recorded with two HBM WA100 (S/N 0324141 and 0324144) in pushing and two HBM W50K (S/N 8807 and 8072) inductive sensors in pulling direction, the displacements of which were averaged. The pressure of the hydraulic fluid in the circuit for the normal force

was also measured with a 500 bar HBM P4Ak (S/N B155528) pressure sensor to validate the data of the normal force sensor.

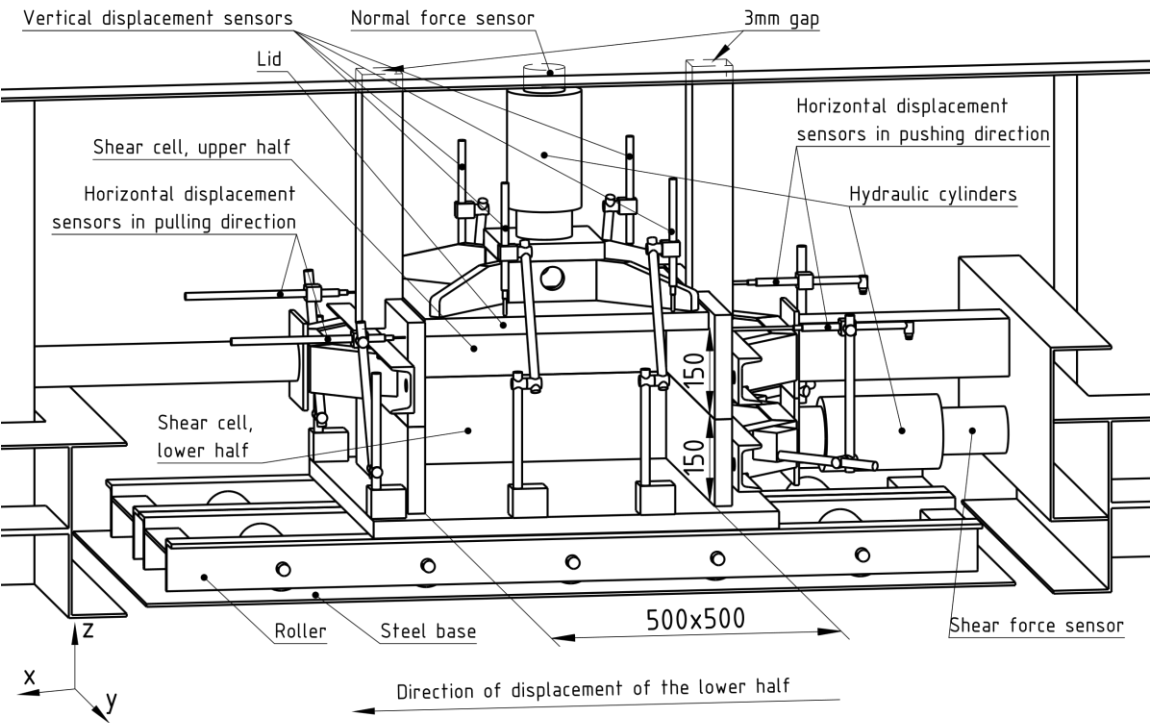


Fig. 1. Simplified 3D schematic of the large-scale shear box apparatus and the applied coordinate system. The right walls of the shear cell are hidden to show the inner dimensions [mm] of the box.

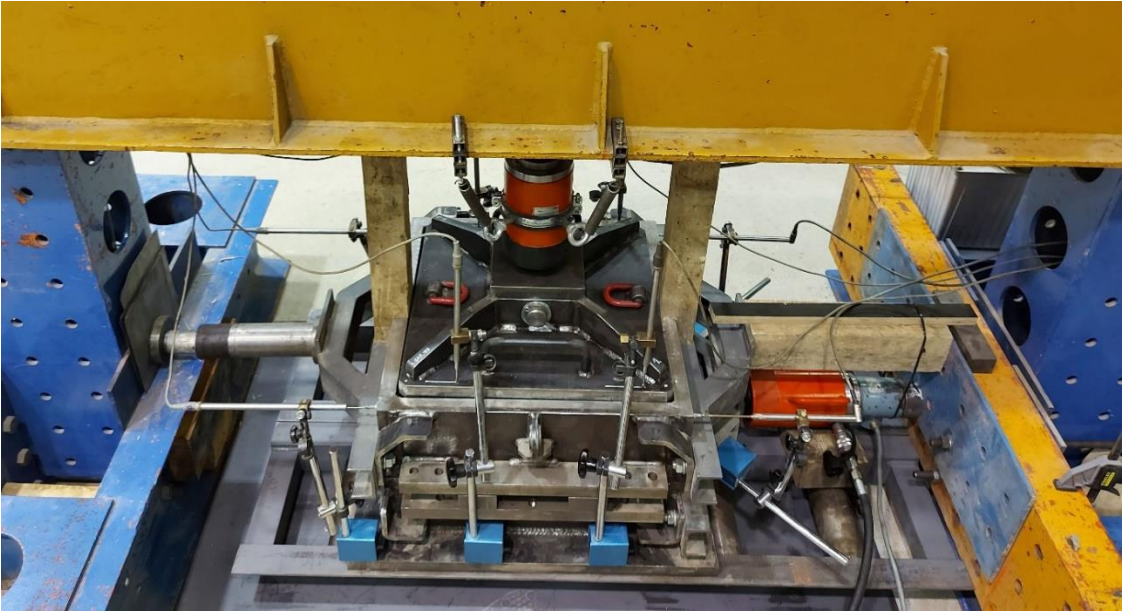


Fig. 2. Photograph of the large-scale shear box apparatus.

2.2 Image recognition

It is challenging to capture the displacement field of flowing granular media, especially inside a non-transparent container. There are methods to record the movements of tracer grains either equipped with sensors [37–39] or made radioactive [40,41]. Smaller samples can be digitized with computed tomography (CT) [42,43]. In contrast with these methods which require sophisticated equipment, this study introduces a much simpler solution. The shear cell used in this study was completely new, and the stones left characteristic scratch marks on the inner side of its walls. Photographs were taken of these scratches, and 2D displacement fields were computed using GIMP and the Image Processing Toolbox of MATLAB. Naturally, these displacement fields only offer averaged, qualitative results, and give insight to the grain trajectories at the wall, where boundary effects acting on the assembly are present, but they still contain valuable information.

The image processing steps are represented in Fig. 3. (1) Firstly, a photograph was taken, and the boundaries of the evaluated wall were identified. (2) Then, the distortions of the photograph were compensated to get a planar image of the wall. The weld beads at the sides and the top region which were in contact only with the top lid (i.e. not with the grains) were also marked. (3) The weld beads and the top sections were cropped, and the image was converted to monochromatic, where the scratches were marked with pixels of high intensity (white), and the background with pixels of low intensity (black). (4) The scratches were identified (black regions), segmented, and their corresponding ellipses were calculated, which have the same second normalised second central moments as the regions. The lengths of the ellipses' major axis estimated the lengths of the scratches, and their orientations defined the scratch orientations. These are represented by red arrows. (5) The image recognition process reveals the orientation of the scratches, but not their direction (i.e. the direction of the displacement's horizontal component). It was assumed that the grains in the upper half moved

‘forwards’ in relation to the shear cell (in the direction of the velocity of the lower half) and they moved ‘backwards’ in the lower half. Therefore, in the fifth step, the orientations of the vectors were adjusted accordingly. The displacement of the shear cell lower half is about one order of magnitude greater than the length of the scratches. To make the diagrams easier to read, it was decided to represent the relative (to the corresponding half of the shear cell, which was equal to the length of the scratches) displacements and not the global ones, i.e., the displacement of the lower shear cell was not accounted. The whole area was divided into rectangular binning domains with equal sizes (20x21.43 mm, grey grid) and the scratch vectors were averaged in each domain resulting to the blue vectors positioned at the centroid of the domains. Only the scratch vectors with length greater than 3 mm were accounted in the mean computation, and mean vectors were only calculated for those domains in which minimally 3 scratches occurred. The lower and side boundaries of the shear cell, which provided no sufficient data and were cropped in step 2 of the procedure. (6) In the last step, the domain boundaries were removed, and the representation of the shear box displacement was added. A further adjustment was made to the vector orientations. It is very unlikely that the largest displacement component of grain found in the upper section of the shear box points downwards. It is more probable that it moves upwards with a slight backwards component. Hence, the vectors that made angle with the x axis between -45° and -90° were flipped (i.e. rotated by 180°). Such vectors are marked by the two ellipses in the 6th step of Fig. 3.

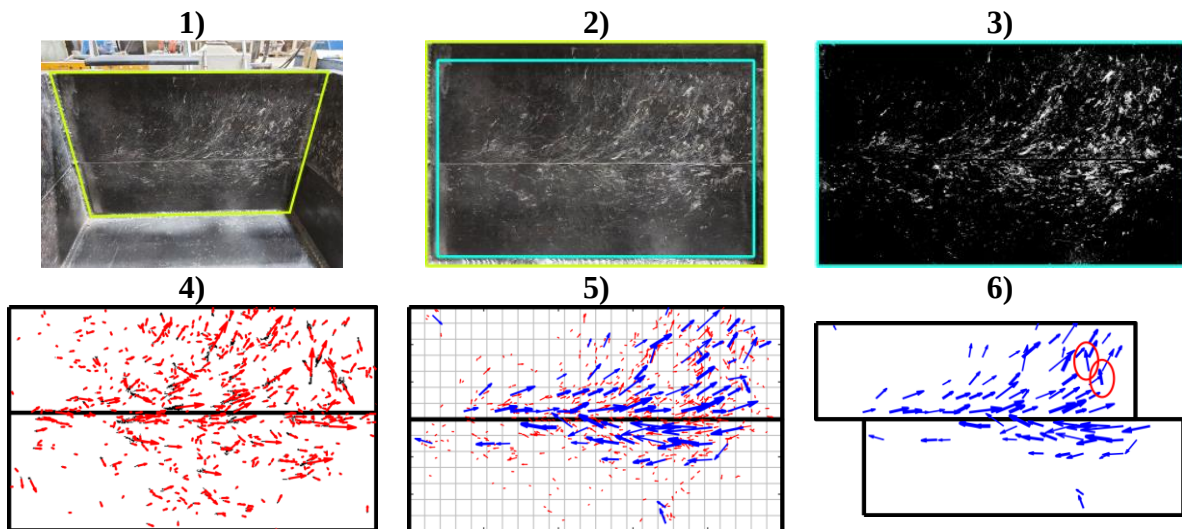


Fig. 3. Steps of scratch-recognition image processing on the inner side of the shear cell: 1) original photograph, 2) stretch and crop, 3) binarize into monochromatic image, 4) recognise scratch marks, compute their magnitude and orientation 5) domain creation and average computation, 6) final diagram with averaged vector fields.

2.3 Composition of assemblies

The grains tested in the large-scale shear test were selected from larger assembly according to the classification method introduced in Part I. of the companion papers, using bar sieves (uniquely manufactured) and two shape index callipers (S/N HS312150172, S/N HS311011022). Three assemblies were created from the four different stone types. The target compositions based on mass percentage (m%) were:

- *compact assembly*: 50 m% C31.50/40 and 50 m% C40/50;
- *non-compact assembly*: 50 m% NC31.50/40 and 50 m% NC40/50;
- *mixed assembly* (10:3 compact-to-non-compact grain mass ratio): 11.5 m% NC31.5/40, 11.5 m% NC40/50, 38.5 m% C31.5/40, 38.5 m% C40/50.

In the original, larger assembly, the proportion of the non-compact grains was much lower than the compact ones, therefore about 2.5 tonnes of standard railway ballast were processed until the needed amount was collected. During railway construction, railway ballast

is washed before its application to improve frictional properties between particles via the removal of fines, therefore the investigated aggregates were also cleaned. Because industrial equipment was not accessible during the experiments, each grain was manually cleaned under running water using a simple root brush. The stones were placed into the shear cell by hand and were not compacted to avoid layers with different porosity. The second aim with this filling method was to mimic the gravity deposition process frequently applied in simulations. At the end, the top of the assembly was levelled by hand to get more contact points thus a more even force network with the lid of the box. With the applied filling method, the grains in the compact and mixed assemblies had evenly random orientations and the effect of walls was limited as well, because only 1-2 layers of grains aligned with them in their near vicinity (visual inspection). However, grains in the non-compact assembly had high tendency to align with the walls and each other, which made hard to place them in evenly random orientations. A similar behaviour is also expected in industrial scales, when the grains align with each other due to vibrations and disturbances, resulting an assembly with a highly directed fabric. Therefore, special attention was taken when the box was filled with the non-compact assembly: the grains were laid on their flat sides, similarly to how they would align in a larger sample without walls. With this filling method, the shearing happened in the weakest plane of the assembly, when the normal of the flat sides of the grains are orthogonal to the shearing direction. This alignment is favourable, because in realistic, complex load conditions, such an assembly is also likely to fail along its weakest plane.

During the large-scale shear box tests, each type of assembly was tested under 4 different nominal normal loads (20, 40, 60, 80 kPa for the compact and 20, 30, 40, 50 kPa for the non-compact and mixed assemblies). The final normal stresses were slightly higher because the weight of the upper shear cell half was added to it and showed some scatter due to the analog and manual hydraulic system. Three repetitions were made at each load level,

resulting in 12 tests for each aggregate and 36 measurements altogether. The assemblies were reused in the tests corresponding to the same type of composition, because it would require too much effort to sort 12 x 2.5 tonnes railway ballast. Therefore, measures were taken to guarantee comparable but randomised results. The grains were taken out from the shear cell, mixed, and poured back between each test, to generate different initial packings of the same grains. The fines and those grains whose breakage was clearly visible (e.g. broken into half or into multiple pieces) were removed from the assembly and replaced with fresh ones to maintain the same size and form distribution throughout the tests. The normal loads were chosen to keep the breakage rate low (< 3 m% in each test). The size and shape ratios, the total mass and grain number were known at the beginning (*initial*) and were measured at the end (*final*) of all test series for each assembly (Table 2). The average density of the grains was measured using Archimedes' principle and was found to be $\rho_s = 2541 \pm 55 \text{ kg/m}^3$ (two standard deviations, 25 repetitions were made with 2-3 kg samples, the two smallest and two largest values were removed). Using the mass of the assemblies (m_s [kg]), and the inner volume of the shear cell (V_c [m³]), the porosity (ϕ , [-]) was computed as:

$$\phi = \frac{V_c - \frac{m_s}{\rho_s}}{V_c} = 1 - \frac{m_s}{\rho_s V_c} \quad (1)$$

If we omit the error of the mass and volume measurements and the errors due to the limited precision of the measurement equipment, which are much smaller than the uncertainty of the density ($\delta\rho_s = 55 \text{ kg/m}^3$, approximated by two standard deviations), the uncertainty of the porosity for small deviations is:

$$\delta\phi = \sqrt{\left(\frac{\partial\phi}{\partial\rho_s}\right)^2 (\delta\rho_s)^2} = \frac{m_s}{\rho_s^2 V_c} \delta\rho_s \quad (2)$$

The size of the grains decreased during shearing due to the breakage of their corners: at the end of all 12 tests with each assembly, the ratio of the 22.4/31 grains increased from 0 m%

to 4.06 m%, 12.05 m% and 4.41 m% in the case of the compact, non-compact and mixed assembly, respectively. All compact grains remained compact in the compact assembly, however 10.58 m% of the non-compact grains become compact in the non-compact assembly, which shows that the non-compact grains tend to become compact when they break. This observation is in line with the theory of Buscarnera and Einav [44], who proposed that the shape of the grains tend towards a not too compact ($b/a = c/b \approx 0.70-0.80$ with the investigated mechanical parameters) when they break. Contrarily, the ratio of the compact grains had a slight decrease from 76.84 m% to 74.74 m% in the mixed assembly. The ratio of the non-compact grains did not decrease, because they tended suffer bulk breakage in the mixed assembly, therefore they were removed and replaced with new ones. A few compact grains broke as well, and they might have been replaced with non-compact ones which explains why their proportion increased. Despite the small differences in the composition of the assemblies between each test, the shear strengths did not show any progressive trend (i.e. the shear strength was not affected by the number of the test and varied randomly), therefore the results were decided to be comparable.

Table 2. Initial and final aggregate properties.

Assembly		Compact m% (pc%)			Non-compact m% (pc%)			Total mass	Total grain	Porosity
		22.4/31	31.5/40	40/50	22.4/31	31.5/40	40/50	mass	number	[-]
		.5			.5			[kg]		
Compact	initial	0	50.18 (61.82)	49.82 (38.18)	0	0	0	109.326	1079	0.455 ±0.012
	final	4.06 (6.83)	48.30 (57.53)	47.64 (35.64)	0	0	0	96.762	996	0.462 ±0.012
Non-compact	initial	0	0	0	0	49.96 (63.55)	50.04 (36.45)	109.214	1306	0.442 ±0.012
	final	1.88 (3.10)	4.40 (4.46)	1.30 (0.80)	7.99 (12.81)	35.81 (43.68)	48.62 (35.16)	104.854	1257	0.438 ±0.012
Mixed	initial	0	38.39 (45.57)	38.45 (27.07)	0	11.54 (16.86)	11.62 (10.50)	104.24	1038	0.474 ±0.012
	final	3.09 (4.70)	29.40 (35.13)	42.25 (31.31)	1.32 (2.35)	11.09 (15.75)	12.85 (10.76)	100.184	1022	0.470 ±0.012

*The mean properties were calculated from sieving data before and after the test series with each type of aggregate, excluding porosity, which was known in each test (m%: mass percent, pc%: piece percent).

3. Results and discussion

3.1 Uniaxial compression stage

Each shear test started with the application of the normal load. During this compaction phase, neither the velocity, nor the force increment was constant, therefore force-displacement graphs could not be recorded. However, the compactions after the application of the normal loads contain valuable information. Fig. 4 shows the normal stresses [kPa] and normal displacements [mm] for each assembly and load level. The data of the corresponding repeated tests were averaged. Standard deviations were not computed due to the low number of repetitions (3 for each setting). It can be seen that the grain form had no noticeable effect on the compressive behaviour of the assemblies in the measured load ranges. The relationship between the normal stress and normal displacement is roughly linear. Grain breakage was not experienced at this phase of the test.

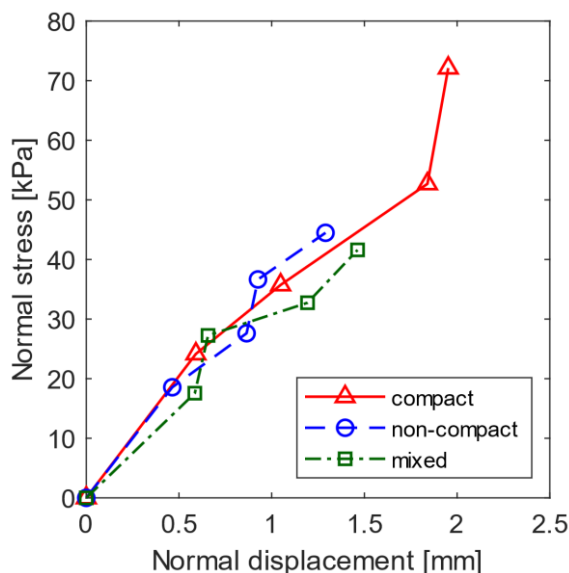


Fig. 4. Averaged normal stress [kPa] vs. normal displacement [mm] values of the three different assemblies at the end of the initial compaction phase of the shear box tests (three repetitions at each normal stress).

3.2 Shearing of the assembly

The shear behaviour of the assemblies in individual tests was compared at 44 ± 2 kPa normal stress. (The normal stress had small variations due to the tolerance of the manual hydraulic system. For the chosen three tests, two standard deviations of the variation are computed.) Typical results for each type of assembly can be seen on Figs. 5-8. The shear stress [kPa] shown in Fig. 5, Fig. 6 demonstrates the average normal displacement of the lid [mm] and Fig. 8 indicates change in its angle [$^{\circ}$] vs. the shear displacement [mm]. The apparatus was originally designed to be able to attain 60 mm of displacement, but it turned out to be capable of larger movements with some modifications. The displacement sensors were replaced and the screws to create the gap between the two shear box halves were removed, because they were not necessary. The tests were continued beyond that value until a physical limit was reached (e.g., the cell clashed with one of the sensors or a sensor stand). There were slight differences in the setups between the measurement due to the reposition of the displacement sensors hence the maximal shear displacement also varied. The normal displacement sensors failed at about 30-40 mm shear displacement during the 44 ± 2 kPa compact tests, therefore the corresponding curves on Fig. 6 and Fig. 8 are shorter.

The development of the shear stresses (Fig. 5) showed a roughly linear increase, followed by a distinctive point indicating material failure (e.g., see the compact assembly at about 42 mm shear displacement), after which shear stress oscillated about a constant value. This behaviour corresponds to a loose assembly. The material showed compression at the beginning of the shearing, which turned into dilatational behaviour at about 10 mm of shear displacement, after reaching a minimum at height at about 5 mm shear displacement. It is interesting to note that this pattern usually belongs to dense granular media which is the opposite what the shear stress results show. This behaviour is similar to the literature results e.g. [26,33]. The only difference is that, in the literature, the shear stress had slight

monotonous decrease after reaching the peak shear strength instead of keeping a constant average value. The lid rotation around the x axis (Fig. 7) did not show any monotonous trend. Although it became -1° in the case of the mixed assembly at the studied test, other test showed smaller and random deviations from zero. However, the lid rotation around the y axis (Fig. 8), increased linearly in every case.

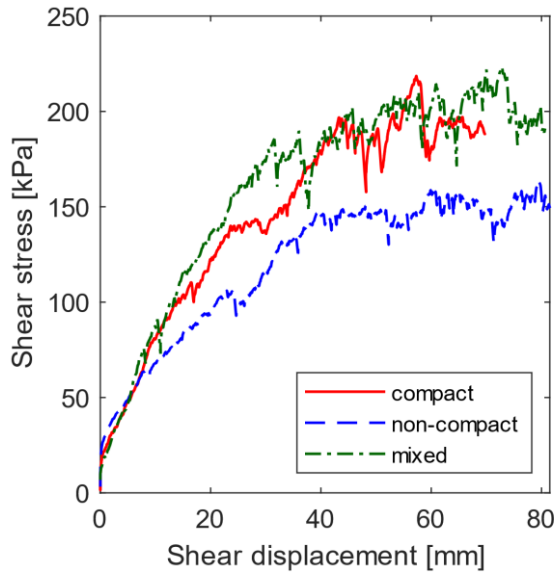


Fig. 5. Shear stress [kPa] – individual shear displacement [mm] graphs for a compact (2nd from 3), a non-compact (3rd from 3) and a mixed assembly (3rd from 3) at 44 ± 2 kPa normal stress.

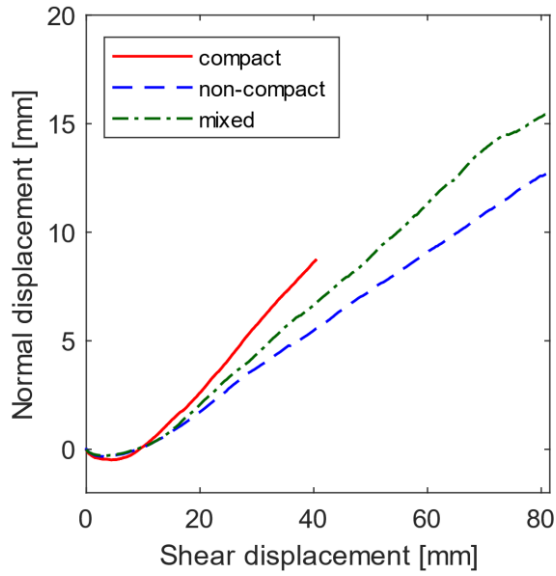


Fig. 6. Normal displacement [mm] – shear displacement [mm] graphs for a compact (2nd from 3), a non-compact (3rd from 3) and a mixed assembly (3rd from 3) at 44 ± 2 kPa normal stress.

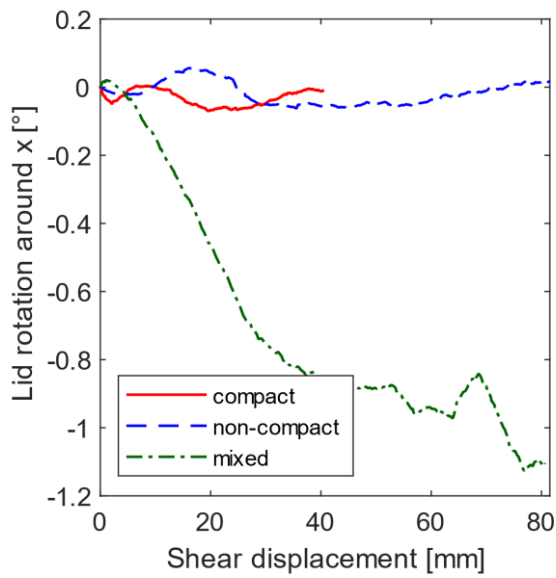


Fig. 7. Lid rotation around x axis [°] – shear displacement [mm] graphs for a compact (2nd from 3), a non-compact (3rd from 3) and a mixed assembly (3rd from 3) at 44 ± 2 kPa normal stress.

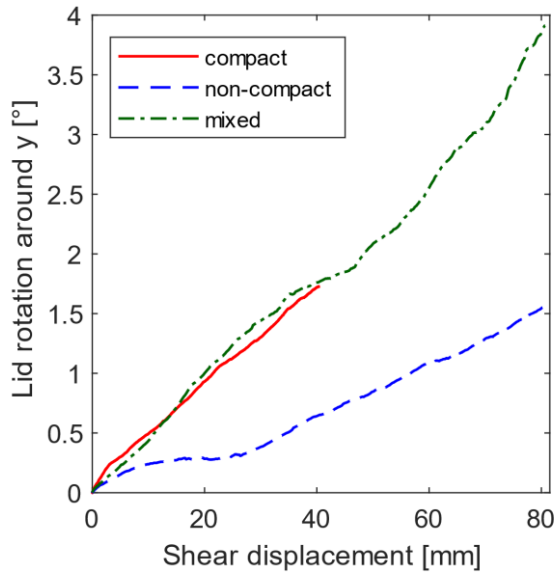
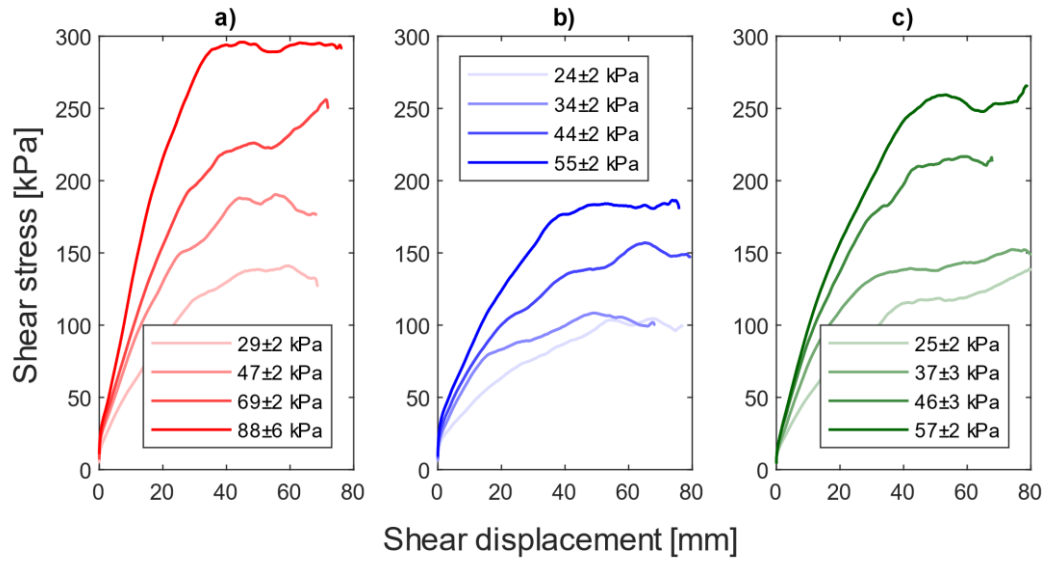


Fig. 8. Lid rotation around y axis [°] – shear displacement [mm] graphs for a compact (2nd from 3), a non-compact (3rd from 3) and a mixed assembly (3rd from 3) at 44 ± 2 kPa normal stress.

Because the individual tests showed high amount of scatter, averaged and smoothed graphs were also computed to make the comparison of the shear behaviour of different assemblies and load levels easier. Firstly, the datapoints were interpolated to have common shear displacement values, then their mean average was computed. The averaged graphs were then smoothed by computing their moving average. The results are shown in Fig. 9-12. The oscillations, which were caused by grain breakage and sudden rearrangements of the assembly, disappeared in the smoothed graphs.

The normal stresses between different tests were not exactly the same (Fig. 9-12) (and differed from the normal stresses in the individual tests as well), because their value could not be precisely adjusted due to the manual hydraulic system, but the results are still comparable, due to the small amount of the differences. The shear stress increases with increasing normal stress (Fig. 9), as expected. The normal displacement (Fig. 10) and the lid rotation (Fig. 12) decreased slightly for increasing normal load.

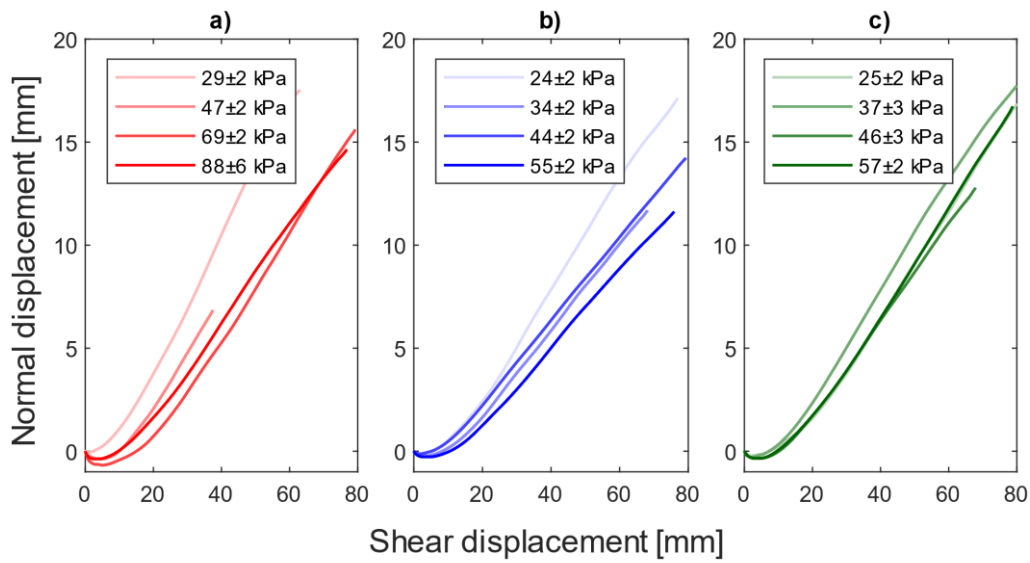
Regarding the effect of grain from, the mixed assembly exhibited the highest shear strength (Fig. 9) considering the normal stress and the compact was the second. This proves the hypothesis that the non-compact grains strengthen the assembly at the studied load level up to a certain ratio. The non-compact assembly was the weakest. This can be attributed to the fact that the grains were highly oriented (it was an observation that flat grains tend to naturally align that way, and the same orientation is expected in bigger assemblies, especially if they were subjected to vibrations), and the shearing happened in the weakest direction of the assembly, therefore sliding planes could be easily developed without significant interlocking of the non-compact grains. Grain form had no noticeable effect on the compaction-dilation of behaviour (Fig. 10), but it affected the y component of the lid rotation (Fig. 12). The lid rotation was the highest for the non-compact assembly, the lowest for the mixed assembly and in between the two for the compact assembly. This is exactly the opposite of the shear strength behaviour, however it would require further analysis to be able to state that higher shear strength always comes with lower lid rotation. The averaged results of the lid rotation around the x axis (Fig. 11) also shows that there were no monotonous trend in the variation of that component.



387

388 Fig. 9. Averaged shear stress [kPa] – shear displacement [mm] graphs for all test at different

389 normal stress levels: a) compact, b) non-compact, c) mixed assembly.



390

391 Fig. 10. Averaged normal displacement [mm] – shear displacement [mm] graphs for all test at

392 different normal stress levels: a) compact, b) non-compact, c) mixed assembly.

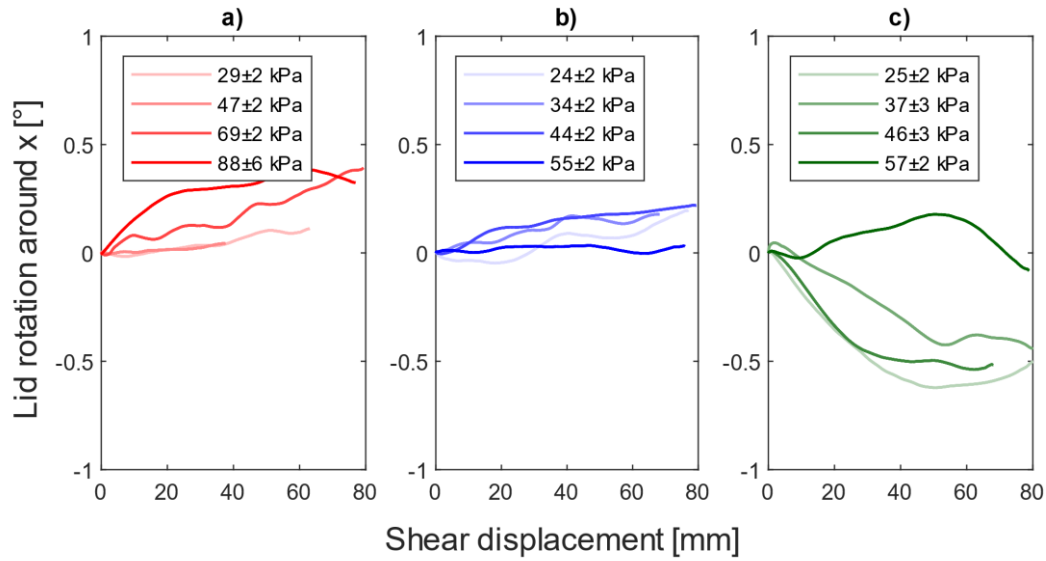


Fig. 11. Averaged lid rotation around x axis [°] – shear displacement [mm] graphs for all test at different normal stress levels: a) compact, b) non-compact, c) mixed assembly.

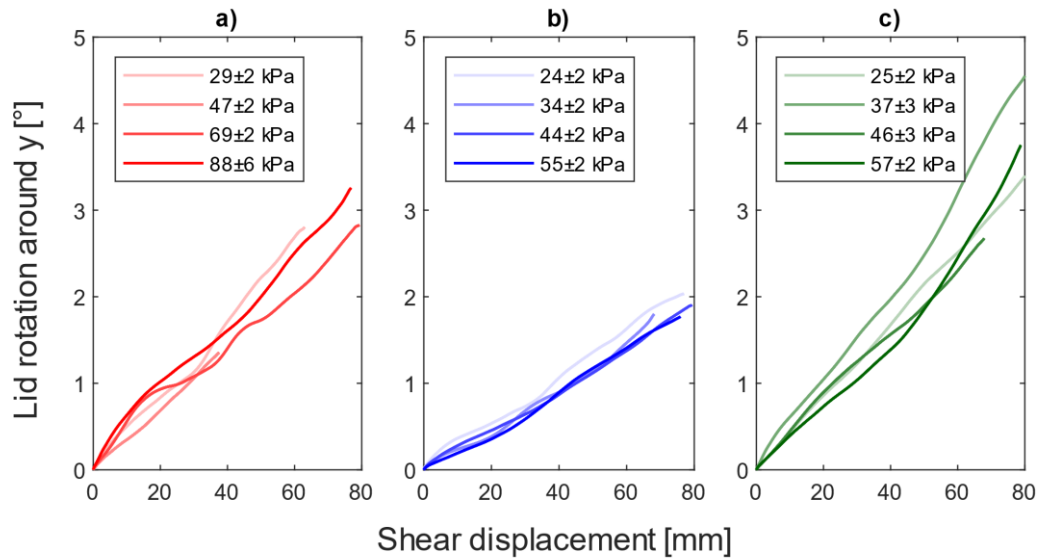


Fig. 12. Averaged lid rotation around y axis [°] – shear displacement [mm] graphs for all test at different normal stress levels: a) compact, b) non-compact, c) mixed assembly.

Fig. 13 shows the measured shear strengths [kPa] of each assembly at each normal load [kPa]. The strengths were calculated in two ways: Fig. 13 a) shows the maximum shear stresses and the corresponding normal stress at that moment, while Fig. 13 b) represents the

averaged shear and normal stresses from failure of the assembly until the end of the test. The error bars represent two standard deviations. Mohr-Coulomb lines were fitted on the datapoints, whose internal friction angle and apparent cohesion values are listed in Table 3. Note that according to Xu and Xu [45], the Mohr-Coulomb criterion cannot describe the shear strength well when particle breakage is considered. However, this criterion was applied in this study because the proportion of broken grains was low in all tests.

The mixed assembly had the highest internal friction angle with 77.63° ($R^2 = 0.79$) for the maximum shear stress, and 77.05° ($R^2 = 0.83$) for the mean shear stress computation method, proving the hypothesis, that the mixed assembly has the greatest resistance against shear. The non-compact assembly had the second highest friction angle with 72.04° ($R^2 = 0.83$) and 71.59° ($R^2 = 0.84$) value, and the smallest values belonged to the compact assembly with 69.89° ($R^2 = 0.87$) and 68.83° ($R^2 = 0.89$). The mixed and non-compact assemblies had apparent cohesions close to zero, especially for the averaged results, which is expected in the case of cohesionless materials. However, the compact assembly had a much higher apparent cohesion of 74.58/59.81 kPa, making it the second strongest material in the studied load region despite that it had the lowest internal friction angle. Compared with literature data of similar railway ballast assemblies (50.1 - 56.3° for Coetzee [26], 53.5 - 64.6° for Suhr et al. [27], 53.5 - 64.6° for Linero-Molina et al [25], 31° for Huang and Tutumluer [28] and 48 - 65° for Indraratna et al. [33]), the internal friction angles are higher in this study than any of the literature data. The most possible reason for that is all of the studies in literature used real or scaled-down real railway ballast assemblies. Contrarily, here all grains were thoroughly classified and cleaned, and the assemblies were artificially assembled to have the most amount of control over particle size and form distribution. The smallest grain sieve size was 22.4 mm, but the major proportion of the grains were between 31.5 and 50 mm, therefore

fines were not present in the tests. The ballast material (andesite) was also different than in
 any of the previously conducted experiments.

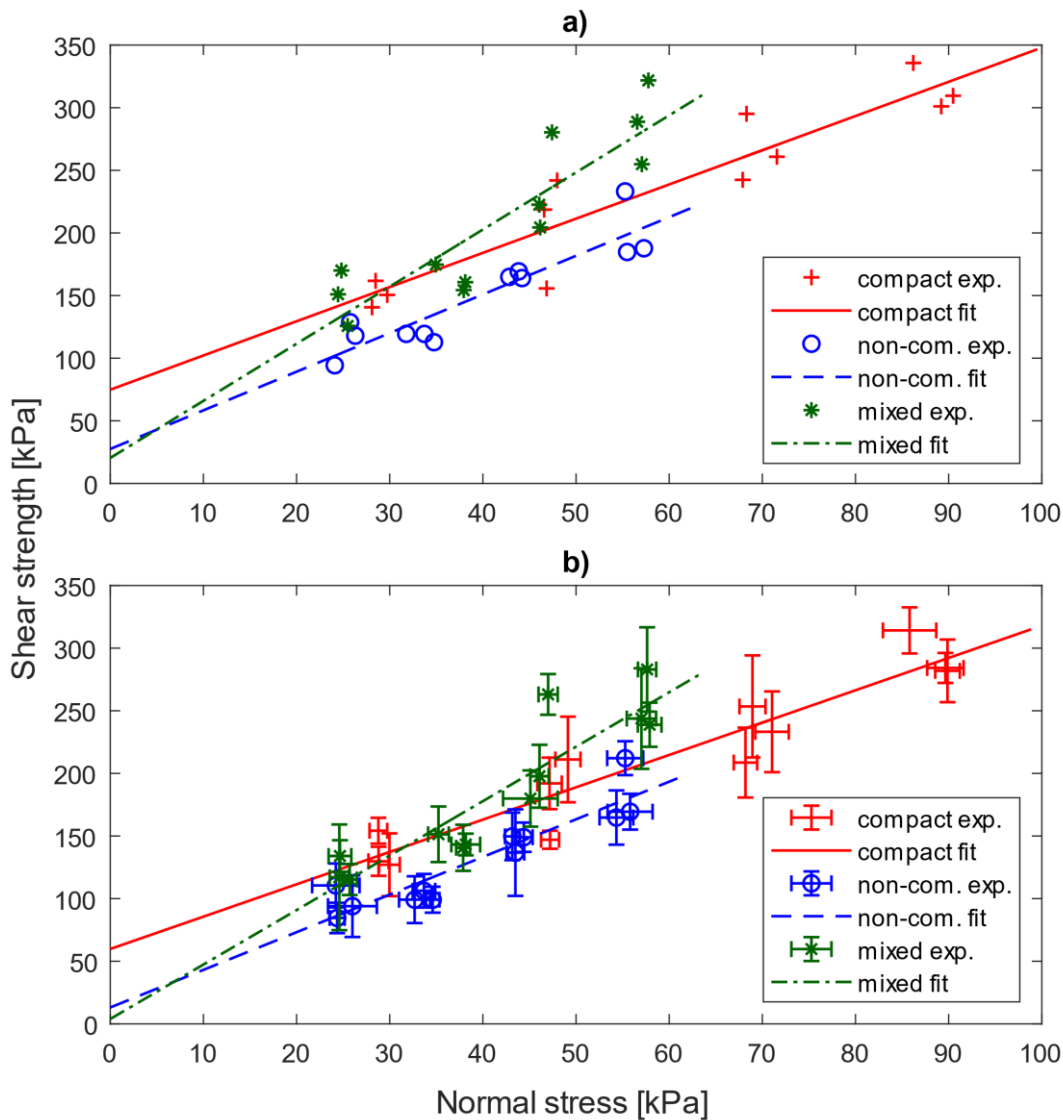


Fig. 13. Mohr-Coulomb failure envelopes for different assemblies, computed from the a)
 maximum shear stress and the normal stress at this stress, b) the averaged shear stress after
 yield and the averaged normal stress after that point.

Table 3. Mohr-Coulomb failure properties of each assembly.

Assembly type	Shear strength computation method	Internal friction angle [°]	Apparent cohesion [kPa]	R ²
Compact	max.	69.89	74.85	0.87
	mean	68.83	59.81	0.89
Non-compact	max	72.04	27.54	0.83
	mean	71.59	13.13	0.84
Mixed	max.	77.63	20.37	0.79
	mean.	77.05	3.94	0.83

3.3 Grain breakage

The mass of the crushed grains and fines was measured to examine if breakage was kept low during the tests. Fig. 14 shows the average broken masses per normal stress and assembly (standard deviation was not computed due to the low repetition number, which was 3). The compact assembly had the least amount of breakage, even though it was subjected to higher loads than the non-compact and mixed assembly. The non-compact assembly suffered the most breakage, which is not surprising as it was made of vulnerable, mostly flat grains. The mass of broken grains in the mixed assembly was almost as high as the fully non-compact assembly. Furthermore, it was observed that the majority of the broken grains were non-compact. Linking this to the high shear strength of the mixed assemblies, the following hypothesis can be made: the non-compact grains are found in between the compact grains and provide interlocking. That is why, this assembly has the highest internal friction angle. However, due to the same mechanism, the non-compact grains are subjected to high forces and break first, in comparison to the compact ones.

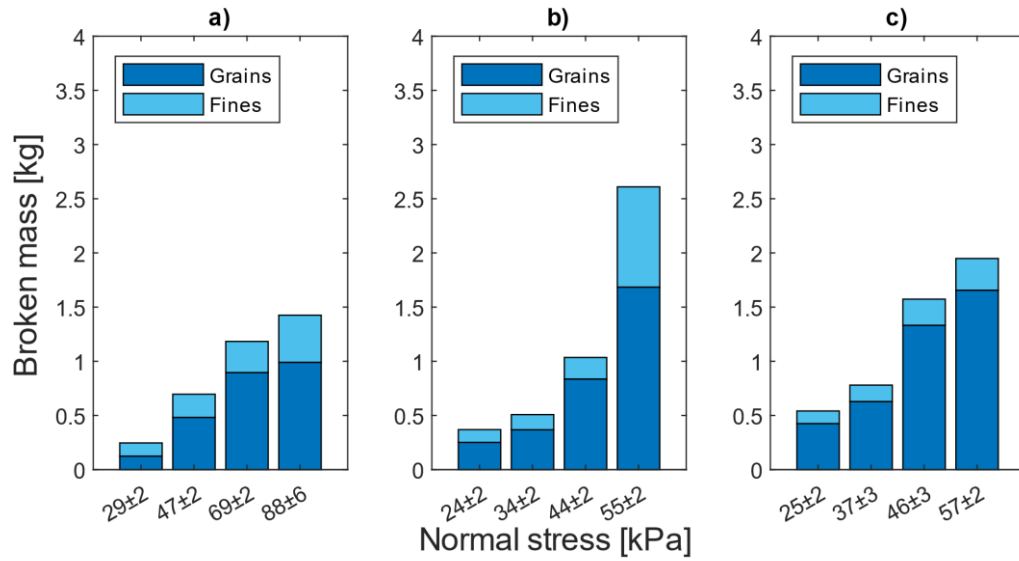


Fig. 14. Average mass of broken grains and fines [kg] per normal stress [kPa] for a) compact b) non-compact and c) mixed assemblies.

The breakage patterns of the grains contain valuable information for the development of DEM models. 149 broken grains were recovered from which 144 split into two halves. This split was asymmetric in 89 cases (Fig. 14 a) and went through roughly the centroid 55 times (Fig. 14 b). The rest 5 pieces of the stone had minimum two perpendicular splitting planes (Fig. 14 c), similarly to the breakage model proposed by Eliáš [46].

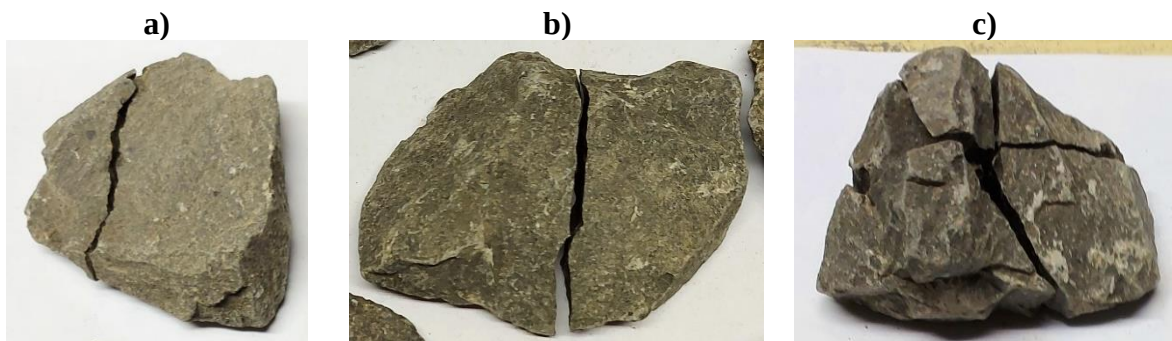


Fig. 15. Different breakage patterns: a) asymmetric split of a flat, b) split through the centroid of a flat c) split along two perpendicular planes of a compact grain.

3.4 Grain trajectories

The scratch vector fields can be seen in Fig. 16. Photographs were taken after the tests with the compact assembly (Fig. 16. a, b), which were the first one in the test series, and after all measurements (Fig. 16. c, d). The displacement fields show good correspondence with the literature data of the DEM simulations discussed in the introduction (Section 1) and represent how far the flow is from the ideal simplification, where there is a distinctive shear plane in the middle of the cell and the grains horizontally move along with the halves of the shear cell. In the upper half of the cell, the assembly flowed upwards and in the direction of the lower cell velocity, which caused the rotation of the lid. There were a few regions, indicated by ellipses in Fig. 16, where the grains flowed slightly backwards beside their upward movement. The relative displacements of the grains in the lower half were mainly horizontal. The flowing direction was opposite to the moving direction of the cell according to the diagram. However, it must be kept in mind that the directions of the displacement vectors were adjusted based on literature data and intuition, because they could not be determined from the shape of the scratches.

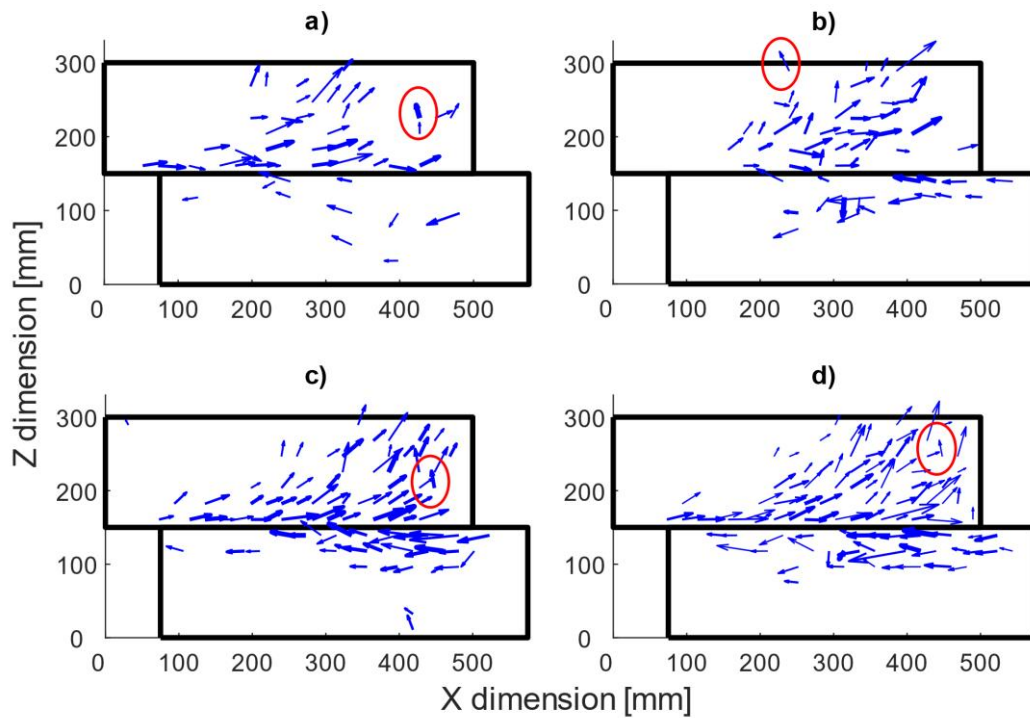


Fig. 16. Mean relative displacement vectors at the inner side of the shear cell walls, computed from scratches: a) left and b) right wall after the tests with compact assemblies, c) left and d) right wall after all tests. The length of the displacements is multiplied by 5 to attain better visibility, and the width of the arrows is proportional to how many scratch vectors they were computed from (min. 3, max 13).

4. Conclusions and outlook

Most of the experimental studies which measure the mechanical properties of railway ballast uses standard aggregate or sort the grains according to their size. In this study, the aggregate was carefully sorted based not only on the size of the grains but on their form as well. The derailed form indices were introduced in the Part I of the companion papers. Then, samples with regulated grain geometries were compiled: a fully compact, a fully non-compact and a mixed one. The shear resistances of the samples were measured using a unique large-scale shear box device. The amount of broken mass was also measured. The overall

displacement field of the grains was computed from the scratches that they have left on the walls of the shear cell using image recognition. The main findings of the study are as follows:

- The grain form had no effect on the compression modulus of the assemblies in the studied normal load range, where particle breakage did not occur.
- The mixed assembly, which contained 23 mass% non-compact (of which the majority of the stones were flat) and 77 mass% compact grains had higher resistance against shear than the assemblies containing only compact or only non-compact (majorly flat) particles. Therefore, mixing grains of different forms can have a favourable effect on the shear strength of a railway ballast assembly.
- Image analysis of scratches left on the shear cell wall proved to be an insightful method to gain qualitative information about the displacement field of the assembly.

This study demonstrated that andesite railway ballast assemblies with mixed particle shape have the highest resistance against shear in the studied load region, where the breakage is not significant. The optimal ratio of non-compact and compact grains is yet to be found in further research with e.g. DEM simulations. The effect of different grain orientations, especially at non-compact assemblies is also to be investigated. The results of this study offer a point of reference and comparison for parameter calibration and digital shape characterisation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit author statement

Ákos Orosz: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Visualisation, Project administration, Funding acquisition, Writing - Original Draft. **Bence**

Szabó: Software, Formal analysis, Visualisation. **Zsolt Farkas:** Investigation, Resources.
Kornél Tamás: Supervision, Project administration, Funding acquisition, Writing - Review
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- A compact, a non-compact and a mixed railway ballast assembly was created.
- The mixed assembly had the highest shear strength.
- The broken masses and failure modes were recorded.
- Displacement fields were computed from scratches on the shear cell walls.