Grain characterisation of fresh and used railway ballast

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Abstract
Ballasted railway track requires regular maintenance to reverse the effects of plastic deformation of the trackbed, which leads to a gradual loss of level. Maintenance is usually by tamping, an aggressive process, which damages ballast grains such that the interval between maintenance interventions steadily reduces with increasing number of tamps. After a certain number of tamps, the ballast is deemed life expired and renewed, with the recovered ballast usually being down-cycled to lower grade uses. The ability to re-use the recovered ballast in the trackbed would make a significant contribution to decarbonising and improving the sustainability of railway infrastructure. This requires detailed knowledge of how the grain characteristics affecting mechanical behaviour differ between fresh and used ballast—specifically grain shape. This paper compares the shape parameters of form, angularity and surface roughness of fresh and used ballast, and proposes a method to synthesize full-size and scaled used ballast for use in laboratory and model tests.

Keywords Ballast shape · Form · Angularity · Surface roughness · Scaled ballast · Ballast re-use

Abbreviations
FFB Full-size fresh ballast
FUB Full-size used ballast
FSyUB Full-size synthesized used ballast
SFB Scaled fresh ballast
SSyUB Scaled synthesized used ballast

1 Introduction and background
Ballasted railway tracks tend to settle with trafficking, and need to be restored to the correct geometry (line and level) from time to time. This is usually achieved by tamping; a process that rearranges the ballast grains, disrupting the old structure and building new grain contacts as it restores the geometry of the track. Such maintenance is costly in terms of both money and time, hence any improvement to ballast performance has the potential for significant savings.

Ballast grains are irregular in shape, which improves their potential for interlocking and hence the ability of the assemblage to resist applied loads. With trafficking and / or tamping, the individual grains tend to wear. They may become less irregular and more rounded, resulting potentially in a loss of interlocking and resistance to load [1]. Train weight and speed, and vibration perhaps exacerbated by unevenness in the rail surfaces and the formation of corrugations, may cause inter-grain impacts and abrasion, promoting deterioration of the ballast. Temperature and pollution may also increase the rate of degradation of ballast grains [2].

Railway track is usually maintained (in terms of its line and level) by tamping. Tamping is an aggressive process in which the track is lifted to the required position and ballast vibrated into place under the sleepers. Tamping restores track geometry by rearranging the ballast grains and is disruptive to ballast structure, causing loosening and breakage [3]. Tamping may also reduce the lateral and longitudinal resistance of the ballast to sleeper movement by up to 25% [4, 5]. While there has been no quantitative study of the effects of tamping on the shape of individual grains or the grain size distribution, but it has been reported that 60% of all fines produced can be attributed to tamping [6] as a result of grain attrition and loss of surface texture and sharp edges.

At present, there is a reluctance to re-use ballast recovered from “mid-life” ballast renewal operations on the basis that its mechanical performance may be compromised. The few studies that compare the shear strength of fresh and used ballast (assuming used ballast to be rounded, less angular and of less surface texture) have yielded inconsistent results. Consolidated undrained (CU) triaxial compression tests on

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ballast previously abraded in an abrasion machine suggested that abrasion (rounding/smoothing) does not lead to significant changes in effective friction angle [7]. However, in cyclic loading experiments, abraded ballasts settled more [4, 5]; this was attributed to the better interlocking properties of fresh ballast arising from its higher angularity, which is reduced during use by the breakage of sharp edges.

One of the reasons for this apparent inconsistency could be the effect of mineralogy; the mineral content can significantly affect the bonds between crystals in ballast grains, hence individual grain strength. Thus, when studying ballast performance and degradation, it may be important to compare ballasts of the same mineralogy. This is not always possible; used ballasts may be decades old and of different mineralogy from fresh ballasts, because of differences in source or processing or changes in standards. The ability to develop materials having the same mineralogy as fresh ballast but the same shape parameters as used ballasts for laboratory testing would therefore be useful in enabling the direct comparison of the mechanical properties of fresh and used ballasts that differ in shape but not mineralogy.

The full size and scaled fresh ballasts used in this study were both obtained from Cloburn quarry, Scotland. The full size used ballast was recovered from locations on the track and its geological origin is unknown. The mineralogy of all three ballasts was determined by X-ray diffraction, with the results given in Table 1. This shows that mineralogies of fresh full size and fresh scaled ballast are similar, while that of the recovered ballast is different. This paper proposes the development of a reduced scale synthesized used ballast from fresh scaled ballast for use in laboratory tests, corresponding to the reduced scale fresh ballast that has been used previously in a range of laboratory tests (e.g. [8 –11]), with the same mineralogy.

The paper first characterizes quantitatively the form, angularity and surface roughness of fresh and recovered full-size ballast; it then uses the results to create a material (scaled, synthetic used ballast, SSyUB) for use in laboratory testing, with the same surface characteristics as full-size used ballast (FUB), by abrading grains in a Micro-Deval apparatus.

Although the Micro-Deval does not macroscopically reproduce tamping, the micromechanical processes involved, i.e. grain-to-grain and grain-to-steel impact and abrasion, are similar (e.g. [12]); and it is shown in this paper that the effect is the same. In developing the scaled synthetic used ballast, the paper quantifies the evolution of damage (roughness) from fresh to used ballast. These data can be used to inform grain specifications in DEM analyses to assess the effects of mechanical abrasion on ballast behaviour and the potential for re-using recovered ballast, either on its own or in combination with fresh ballast. Reusing ballast has clear carbon, sustainability, and cost benefits.

## 2 Grain shape

Grain shape is conventionally described by means of three independent parameters. In decreasing order of scale, these are form (essentially, an aspect ratio); deviation from an ideal geometrical figure (commonly termed angularity or roundness); and surface texture or roughness [13]. A useful summary of these, and common methods of measurement, is given by [8].

### 2.1 Form

Quantifications of form are almost always based on the measurement of at least two of the longest ($L$), intermediate ($I$) and smallest ($S$) dimensions. Two approaches adopted in this paper, based on two parameters between them or each involving all three principal dimensions, are summarised in Table 2. Methods based on a single parameter involving all three dimensions are less satisfactory, because two of the dimensions (and hence the form) can vary and still give the same result.

### 2.2 Deviation from an idealised geometrical figure ("angularity")

A grain can be spherical in form (i.e. $S = I = L$), yet highly angular in the sense that its surface deviates significantly from that of the idealised geometrical figure (sphere). Various methods of quantifying this deviation have been proposed, often based on the ratio of the actual volume, surface area or perimeter in a 2D view containing the longest ($L$) and intermediate ($I$) dimensions to that of a circumscribing circle (3D: sphere) or ellipse (3D: scalene ellipsoid). Some of the

| Ballast type          | D10, mm | Source                        | Orthoclase % | Plagioclase % | Quartz % |
|-----------------------|---------|-------------------------------|--------------|---------------|----------|
| Used (recovered), full size | 30      | Unknown, possibly various     | –            | 20            | 22       |
| Fresh, full size      | 30      | Cloburn                       | 14           | 55            | 20       |
| Fresh, scaled         | 12      | Cloburn                       | 20           | 44            | 33       |
more popular are summarised in Table 1. This parameter is
often referred to as “angularity” or (potentially confusingly,
given the use of the same term in the Zingg plot) “spheric-
ity”. In this paper, angularity is calculated as the difference
between the volume of the true shape and that of the equiva-
lent scalene ellipsoid, normalized by the true volume [15].
This is explained in more detail in Sect. 3.2.

2.3 Surface roughness

Surface roughness is the smallest scale indicator of grain
shape. It is a measure of micro scale asperities and surface
irregularities. It may influence properties such as fracture
toughness [16] and fatigue resistance [17]; and governs the
mechanical properties of a surface such as inter-grain fric-
tion, which may have a threshold effect on the bulk effective
angle of friction if the mode of relative movement between
grains changes from rolling to sliding. Recent analytical
models and simulations enable quantitative prediction of the
inter-grain friction from knowledge of the power spectral
density of the surface topography [18]. Standards and codes
for measuring surface roughness include ASME B46.1, ISO
4287, ISO 25178 and SEMI MF1811. The methods and
techniques used in this Paper are described in Sect. 3.3.

3 Methods

3.1 Form

20 ballast grains from each of the four size fractions
defined by the 22.4–31.5 mm, 31.5–40 mm, 40–50 mm and
50–62.5 mm sieve sizes were selected at random (80 grains
in total). Grains were scanned using a 3D EinScan-S surface
scanner to obtain their associated 3-D point cloud data. The
least-squares best-fit scalene ellipsoid was then found, and
used to determine the principal dimensions $L$, $S$ and $I$. A
typical scanned grain is shown in Fig. 1.

Two different approaches were used to define the form;
(1) the Zingg plot, which characterises the form as flat
(platey), spherical, flat and columnar (bladed) or columnar

| Description | Parameters defining grain form | References | Comment |
|-------------|-------------------------------|------------|---------|
| Zingg plot  | $I/L, S/L$                     | [14]       | Location on a Zingg plot of $I/L$ versus $S/I$ gives a descriptor of form |
| Platyness and Elongation | Platyness ($\alpha$) and elongation ($\zeta$) \[15\] | $\alpha = \frac{2L - S}{L + S + I}$, $\zeta = \frac{L - I}{L + S + I}$ | They quantify the deviation from spherical shape of the grain’s equivalent (i.e. best fit) scalene ellipsoid |

Fig. 1 A typical image of ballast obtained after 3-D laser scanning and meshing

(elongate) according to where the grain lies on a plot of $I/L$ against $S/I$ (see Fig. 5); and (2) the Potticary et al. [15] platy-
ness and elongation parameters (defined in Table 3).

The rationale behind the Potticary et al. [5] approach is as
follows. If $L$, $I$ and $S$ (the longest, intermediate and shortest
dimensions of a grain’s best-fit scalene ellipsoid) are consid-
ered as coordinates in three-dimensional space, the overall
shape of the grain can be represented as a vector $f$ linking the
origin of axes to the point $(L, I, S)$, as shown in Fig. 2. The
grain form is then represented by the direction of $f$, while
the magnitude of $f$ quantifies the grain size.

Considering the intersection, $F$, of $f$ with the “deviatoric”
plane $L + I + S = 1$, normal to the spherical axis $L = I = S$, the
form of each grain is uniquely defined by two in-plane coor-
dinates of $F$ in a frame of reference based on the intersec-
tion $P$ of the deviatoric plane with the spherical axis. The
requirement $L \geq I \geq S$ means that the admissible portion of
the deviatoric plane is defined by the triangle indicated in
Fig. 3. This has vertices corresponding to $I = S = 0$ (needle),
$I = L$ and $S = 0$ (circular disc), and $I = L = S$ (sphere). Transi-
tion along the boundary from a sphere to a needle is as a
prolate ellipsoid with $I = S$; from a sphere to a circular disc
as an oblate ellipsoid with $I = L$; and from a circular disc to
a needle as a flat elliptical disc with $S = 0$.

The two in-plane coordinates needed to define the form are
represented by vectors along the two transition lines from the
sphere point as indicated in Fig. 3. These are in themselves
independent descriptors of grain form termed the platyness (α) and the elongation (ζ); Eqs. (1) and (2) respectively.

\[ \text{Platyness} \quad \alpha = \frac{2(I - S)}{L + I + S} \quad (1) \]

Using the platyness \( \alpha \) and elongation \( \zeta \), the form may be quantified as the deviation of the grain shape from a perfect sphere. The physical significance of these terms can be illustrated with reference to some special cases of an idealized geometric shape (a scalene ellipsoid), as presented in Table 4.

### Table 4 Grain form expressed in terms of platyness and elongation

| Idealised geometric figure | Platyness, \( \alpha \) | Elongation, \( \zeta \) | Notes |
|----------------------------|-----------------------|-------------------|-------|
| Sphere                     | 0                     | 0                 | \( I = L = S \) |
| Prolate ellipsoid          | 0                     | > 0               | \( I > S \) |
| Oblate ellipsoid           | > 0                   | 0                 | \( I = L \) |
| Flat circular disc         | 1                     | 0                 | \( S = 0; I = L \) |
| Elliptical disc            | \( \alpha + \zeta = 1 \) |                  | \( S = 0 \) |
| Needle                     | 0                     | 1                 | \( I = S = 0 \) |

\[ \zeta = \frac{(L - I)}{L + I + S} \quad (2) \]

A detailed explanation and derivation are given in [24]. Using the platyness \( \alpha \) and elongation \( \zeta \), the form may be quantified as the deviation of the grain shape from a perfect sphere. The physical significance of these terms can be illustrated with reference to some special cases of an idealized geometric shape (a scalene ellipsoid), as presented in Table 4.

#### 3.2 Angularity

Following [15], the angularity was quantified as the difference between the actual grain volume and that of the equivalent scalene ellipsoid, normalized by the actual volume: Eq. (3).

\[ \text{Angularity} = \frac{\text{volume}_{\text{true shape}} - \text{volume}_{\text{equivalent ellipsoid}}}{\text{volume}_{\text{true shape}}} \quad (3) \]

#### 3.3 Roughness

A rapid, highly accurate optical 3D surface measurement system, based on an Alicona Infinite Focus variable focus microscope, was used to obtain surface texture scans as
topographical data for roughness measurement. Surface scans (real-space measurement) of small patches of ballast were obtained, and surface roughness computed and compared using power spectral density curves. Data processing comprised removing (1) the mean and (2) the tilt (Fig. 4), prior to power spectral density analysis as described below. The power spectral density represents the roughness of a surface as a function of the spectral frequency, expressed in terms of wavevectors $q_x$ and $q_y$—that is, the number of waves per millimetre in the x and y directions, respectively. The units of the wavevectors $q_x$ and $q_y$ are [L$^{-1}$].

The power spectral density is the Fourier transform of the autocorrelation function of the signal, which consists of only the power (not the phase) of the entire range of wavelengths [18]. It is a surface in spatial frequency space, with units [L$^4$], denoted by $C$. The volume under the power spectral density curve equates to $h_{\text{rms}}^2$, the square of the roughness (Eq. (4)). Different ballast surfaces are compared by plotting the radially averaged power spectral density ($C$) across $q_x$ and $q_y$ against the measured wavevector $q$.

$$h_{\text{rms}}^2 = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} C(q_x, q_y) dq_x dq_y$$

(4)

Damage to ballast grains may occur at a range of roughness wavelengths, from millimetres down to microns. Grain form and angularity govern coarse-scale interlocking of the ballast grains, while surface roughness or texture influences inter-granular friction. Therefore, a full understanding of ballast shape and roughness requires consideration of the scale of observation. The longest wavelength that can be obtained from the surface scan of an area is determined by the maximum patch dimension, $L$ (this corresponds to the smallest wave vector, given by $2\pi/L$). Depending on the size of the patch, the longer wavelengths might be considered to be contributing to angularity rather than roughness, and their components in the PSD are strongly influenced by the underlying shape of the surface patch, as is the roughness measure, $h_{\text{rms}}$. To reduce this effect, an upper cut-off wavelength of 2 mm was chosen and the corresponding, smaller wave vectors were excluded from the calculation of surface roughness.

Ballast topographical data are aperiodic. Therefore, prior to calculation of the PSD, the surface height data was processed using a Welch window to impose a periodicity on the data, as expected by the Fourier transform. A detailed discussion of effects of aperiodicity and potential errors from inappropriate windowing is presented by [18].

### 3.4 Synthesis of used ballast

Simulated used ballast was synthesised using the Micro-Deval apparatus. The Micro-Deval apparatus is usually used to investigate the abrasion resistance of aggregates. It comprises a steel drum into which 1.5 kg of the aggregates under investigation are placed, together with 5 kg of 10 mm diameter steel balls and 2 L of water. The drum is then rotated at 100 rpm for a specified period of time (typically between 95 and 120 min). The abrasion resistance is quantified by the “abrasion loss”, defined as the mass of post-test material passing a 1.18 mm sieve. Previous research has used the Micro-Deval or the Los Angeles Abrasion (LAA) machine to abrade grains to study the effects of degradation on aggregate strength. In the Micro-Deval apparatus, ballast grains undergo (i) gentle degradation as the accumulation of tangential inter-grain displacements affects ballast surface roughness; and (ii) impact loading, causing the loss of the larger asperities thereby affecting grain form and angularity.

![Fig. 4](image-url) **Fig. 4** a Before and b after surface de-tilting of a scanned surface
[7, 25]. It was therefore chosen for this study as likely to be more representative of the effects of tamping, as noted by Deiros Quintinilla et al. (2017). Equal masses of aggregates and steel balls were used, without water; and the effect on the ballast grains was measured at intervals to determine the period of abrasion at 100 rpm required to obtain a material resembling used ballast in terms of its grain surface roughness and shape.

Ten different patches on five ballast grains (2 patches on each grain) selected at random were used to determine the power spectral density and roughness after 5, 30, 60 and 90 min rotation in the Micro-Deval drum at 100 rpm. The patches on each ballast grain were marked with permanent ink so they could be identified for analysis at each stage; the marks were still visible and readily identifiable after each stage of abrasion. After completion of the tests, the grain size distribution and roughness of the ballast from the machine were compared with those of the fresh and used ballast to determine a suitable time period of abrasion that degrades ballast to a roughness equivalent to that of real used ballast.

4 Results and discussion: full-size ballast

4.1 Shape

Ballast shape was analysed using the Zingg plot [14] (Fig. 5) and in terms of Potticary et al. platyness versus elongation [15] (Fig. 6). The platyness versus elongation plot shows a more obvious distinction between fresh and used ballast, with the used ballast generally being closer to spherical in form.

4.2 Angularity

Angularity was quantified as the difference between the volume of the true shape and that of the fitted scalene ellipsoid, normalised by the true volume of the ballast grain [24] (Eq. (3)). In general, the used ballast was less angular than fresh ballast. This can be attributed to the wear of the sharp corners of the grains during loading. The measured angularities of actual and synthesized used ballast are compared in Fig. 12.

4.3 Roughness

Comparison of the power spectral densities of surface scans of fresh and used ballast (Fig. 7) shows that fresh ballast has significantly more surface texture (greater height across the range of wavenumbers investigated) than used ballast.

Power spectral density plots for a particular patch on an individual ballast grain after each elapsed period shown in Fig. 8 indicate a gradual loss of surface roughness with time in the Micro-Deval machine. 90 min of Micro-Deval abrasion of fresh full-size ballast gave a surface roughness equivalent to that of the used full-size ballast shown in Fig. 7.
The Network Rail grain size specification for full size ballast, shown in Fig. 9, is too large for triaxial testing of specimens less than at least 200 mm in diameter; hence a \( \frac{1}{3} \) scale ballast that reproduces the key attributes of fresh ballast mechanical behaviour has been developed [8] and used in standard triaxial and other laboratory tests [9, 11, 26]. Here, the aim is to develop a scaled material representative of used ballast, for use in triaxial tests on 150 mm diameter specimens. There are three stages to this process; (1) quantifying the form of used full-size ballast, (2) generating simulated scaled used ballast, and (3) demonstrating that the synthetic scaled used ballast is representative of the full-size material in terms of its shape. The first of these, together with the feasibility of synthesising full-size used ballast in the Micro-Deval machine, were addressed in Sect. 3.4 (Figs. 6, 7, 12). Below, we describe a process for synthesising scaled used ballast and demonstrate that, relative to the corresponding fresh material, it is representative of used ballast recovered from the track during ballast cleaning.

Synthetic, scaled used ballast was created in the laboratory using the Micro-Deval apparatus in a similar way to the full-size material (Sect. 3.4), using 5 mm diameter (rather than 10 mm diameter) steel balls. The surface roughnesses of full-size and scaled ballast are compared in Fig. 10 (Full-size Fresh and Scaled Fresh) and Fig. 11 (Full-size Used recovered from the field, and Scaled Used, synthesised in the laboratory). Figure 10 shows that the roughness profile of the Scaled fresh ballast is similar to that of the Full-size fresh ballast. Figure 11 shows that the roughness profile of the Scaled synthetic used ballast is similar to that of the Full-size used ballast.

The form and angularity of the \( \frac{1}{3} \) scale material after 90 min’ abrasion are also comparable with those of full-size used ballast (FUB) from the field, are shown in Figs. 6 and 12 respectively. Hence the proposed approach will generate representative scaled used ballast for use in laboratory testing.
6 Conclusions

1. In terms of form, the Potticary et al. [10] platyness versus elongation plot shows a more obvious distinction between fresh and used ballast than the Zingg plot, with the used ballast being generally closer to spherical in form. Average platyness and elongation of full-size fresh ballast (FFB) were 0.20 and 0.15, whereas those of full-size used ballast (FUB) were 0.19 and 0.12 respectively.

2. A 3-D measure of angularity based on the difference in volume between the actual and idealised solid shapes was adopted. The measured angularity ranged from 10–40%. Some grains experience greater loss of angularity in use than others because they were initially more angular, with asperities more prone to damage than those of less angular grains.

3. Power spectral density was used to measure and compare the surface roughness, \( h_{rms} \) of fresh and used ballast. For fresh ballast, \( h_{rms} \) ranged from 35–60 microns, while for used ballast of similar mineralogy \( h_{rms} \) ranged from 15–30 microns.

4. After 90 min of abrasion in the Micro-Deval apparatus, for the particular specimens considered in this study, fresh ballast resembled used ballast in terms of its surface roughness. Significant grain breakage resulting in a measurable change in grain size distribution was not apparent.

5. A simulated, \( \frac{1}{3} \) scale used ballast was produced by abrading \( \frac{1}{3} \) scale fresh ballast grains in a Micro-Deval testing apparatus for 90 min. This process can be adopted to synthesise \( \frac{1}{3} \) scale used ballast for use in laboratory element and model tests.
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**Declarations**

**Conflict of interest** The authors have no conflict of interest.

**Consent to publication** The authors consent to publish this work.

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**References**

1. Network Rail.: Ballast: what is it and why do we clean and replace it every night? (2019). https://www.networkrail.co.uk/stories/ballast-what-is-it-and-why-do-we-clean-and-replace-it-every-night/.
2. Tolppanen, P., Stephansson, O., Stenlid, L.: 3-D degradation analysis of railroad ballast. Bull. Eng. Geol. Environ. 61(1), 35–42 (2002)
3. Aursudkij, B.: A laboratory study of railway ballast behaviour under traffic loading and tamping maintenance. Univ. Nottingham, no. September, pp. 1–234 (2010)
4. Esveld, C.: Improved knowledge of CWR track. In: Interact. Conf. Cost Eff. Saf. Asp. Railw. Track, UIC/ERRI, Paris, pp. 8–9 (1998)
5. Liu, J., Wang, P., Liu, G., Xiao, J., Liu, H., Gao, T.: Influence of a tamping operation on the vibrational characteristics and resistance-evolution law of a ballast bed. Constr. Build. Mater. 239, 117879 (2020)
6. Guo, Y., Markine, V., Jing, G.: Review of ballast track tamping: Mechanism, challenges and solutions. Constr. Build. Mater. 300, 123940 (2021)
7. Kolos, A., Konon, A., Chistyakov, P.: Change of ballast strength properties during particles abrasive wear. Procedia Eng. 189(May), 908–915 (2017)
8. Le Pen, L.M., Powrie, W., Zervos, A., Ahmed, S., Aingaran, S.: Dependence of shape on particle size for a crushed rock railway ballast. Granul. Matter 15(6), 849–861 (2013)
9. Le Pen, L., Bhandari, A.R., Powrie, W.: Sleeper end resistance of ballasted railway tracks. J. Geotech. Geoenviron. Eng. 140(5) (2014)
10. Guo, Y., Markine, V., Song, J., Jing, G.: Ballast degradation: Effect of particle size and shape using Los Angeles Abrasion test and image analysis. Constr. Build. Mater. 169, 414–424 (2018)
11. Nakamura, T., Momoya, Y., Nomura, K., Yoshihiko, Y.: Shaking table test using full-scale model for lateral resistance force of ballasted tracks during earthquake. Procedia Eng. 143(1ctg), 1100–1107 (2016)
12. Deiros Quintanilla, I.: Multi-scale study of the degradation of railway ballast (2018)
13. Barrett, P.J.: The shape of rock particles, a critical review. Sedimentology 27(3), 291–303 (1980)
14. Zingg, T.: Beitrag zur Schotteranalyse (Contribution to ballast analysis). ETH Zurich (1935)
15. PottiCaray, M., Zervos, A., Harkness, J.: The effect of particle elongation on the strength of granular materials. In: 24th UK Conference on Association Comput. Mech. Eng., no. April, pp. 239–242 (2016)
16. Bruzzone, A.A.G., Costa, H.L., Lonardo, P.M., Lucca, D.A.: Advances in engineered surfaces for functional performance. CIRP Ann. Manuf. Technol. 57(2), 750–769 (2008)
17. Proudhon, H., Fouvry, S., Buffière, J.Y.: A fretting crack initiation prediction taking into account the surface roughness and the crack nucleation process volume. Int. J. Fatigue 27(5), 569–579 (2005)
18. Jacobs, T.D.B., Junge, T., Pastewka, L.: Quantitative characterization of surface topography using spectral analysis. Surf. Topogr. Metrol. Prop. 5(1) (2017).
19. Wadell, H.: Sphericity and roundness of rock particles. J. Geol. 41, 310–331 (1932)
20. Krumbeln, W.C.: Measurement and geological significance of shape and roundness of sedimentary particles. J. Sediment. Res 11, 64–72 (1941)
21. Aschenbrenner, B.C.: A new method of expressing particle sphericity. J. Sediment. Res. 26, 15–31 (1956)
22. Sneed, E.D., Folk, R.L.: Pebbles in the lower Colorado River, Texas a study in particle morphogenesis. J. Geol. 66, 114–150 (1958)
23. PottiCaray, M.J.: The Effect of Shape on the Strength of Coarse Granular Material. University of Southampton (2017)
24. PottiCaray, M., Zervos, A., Harkness, J.: An investigation into the effect of particle platyness on the strength of granular materials using the discrete element method. In: Proceedings of 4th International Conference on Particle Methods—Fundamentals and Applications Particles 2015, pp. 767–778 (2015)
25. Deiros Quintanilla, I., Combe, G., Emeriault, F., Toni, J.B., Voivret, C., Ferellec, J.F.: Wear of sharp aggregates in a rotating drum. In: EPI Web Conference, vol. 140, pp. 2–5 (2017)
26. Aingaran, S., Le Pen, L., Zervos, A., Powrie, W.: Modelling the effects of trafficking and tamping on scaled railway ballast in triaxial tests. Transp. Geotech. 15(Febraury), 84–90 (2018)

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