USE OF DIGITAL IMAGING FOR GRADATION AND BREAKAGE OF RAILWAY BALLAST

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ABSTRACT

The foundation of ballasted railway is usually consisted of a graded layer of granular media of ballast placed above naturally deposited subgrade. The ballast layer is responsible for limiting the vertical stress magnitudes applied to the weaker subgrade and also prevents the vertical and lateral train-induced sleeper movements. In recent years, the progressive use of faster and heavier trains has compromised the ability of ballast to resist such movements due to the increased magnitude of ballast breakage (degradation). Therefore, accurate determination of ballast breakage is important. The amount of ballast breakage can be estimated by comparing the gradation (particle size distribution) curves of fresh and degraded ballast, using a ballast breakage index. However, the Australian railway authorities currently rely on the visual inspection for estimating ballast breakage. Despite the fact that the visual inspection is convenient, as it does not require transport of ballast samples or testing, it is subjective and can lead to uneconomical maintenance cycles. In this paper, an attempt is made to utilise the digital imaging technique for gradation analysis and breakage estimation of ballast. The technique is fast and convenient, and can be applied to both the laboratory and field conditions, hence, can be used successfully to replace the visual inspection of ballast breakage.

1 INTRODUCTION

Railway ballast is used to support and restrain the rail tracks; however, over time, the ballast degrades and loses its effectiveness under the influence of train-induced loading. Degradation (breakage) of ballast results in decreased track shear strength (due to the loss of particle angularity and sharp edges), increased track total and differential settlements and reduced track drainage (due to fouling of the degraded fines). These problems have a major impact on track misalignment and derailment, and contribute a significant portion of track substructure maintenance cost. Therefore, accurate determination of ballast breakage is important to decide when the degraded ballast needs to be replaced with fresh ballast.

A number of Australian railway representatives identified that the only method currently used by the Australian railway authorities to judge the ballast breakage is by the visual inspection of ballast samples taken from underneath the sleepers. In this regard, the visual inspection is fast and convenient as it does not require sample transport or ballast testing. However, the visual inspection is subjective and unreliable as it solely depends on the individual experience of the inspecting engineers. Whilst an engineer may identify that the ballast is degraded enough to be replaced, it is difficult to describe the extent of degradation (e.g. low, medium, high). It should be emphasised that whilst the likelihood of track derailment and misalignment in Australia due to ballast breakage is low, the consequences (if occurred) are catastrophic. Therefore, it is unwise that such an important index is determined based on visual inspection alone

In the last few years, digital imaging techniques have been used successfully for analysis of particle shape and size distribution of coarse aggregates. For example, Mora et al. (1998) compared gradation curves of three different types of coarse aggregateusing digital imaging and mechanical sieving. They proposed a simple method for converting the area gradation from 2D images to mass gradation, and good agreement has been obtained between the image analysis and sieve analysis. Kwan et al. (1999) used digital imaging to study the flakiness and elongation of particle shape. Banta et al. (2003) estimated the particle mass of crushed limestone aggregates from 2D images, and developed a multiple linear regression model to predict the particle mass from particle volume and area characteristics. Fernlund (2005) presented a 3D grain size distribution for 10–50 mm size granite by measuring all three axes of particles from 2D images. However, the process was time consuming as the position of the particles had to be manually changed twice to obtain 2D images for measuring all three axes. Kumara et al. (2011) used the area dimensions of particles to develop a particle size distribution curve that gave a good representation of the sieve analysis curve. More recently, Boler et al. (2012) established linkages between ballast degradation and imaging based on aggregate particle shape, texture and angularity indices.

This paper describes the digital imaging technique used for gradation analysis and breakage estimation of railway ballast. A number of experiments were carried out in the laboratory and field, and some factors affecting the digital image processing were investigated including the modelled particle shape, colour of card of sample tray and effect of particle contact. Comparison between the particle size distribution obtained from the digital imagining (image analysis) and mechanical sieving (sieve analysis) is made, and a modified ballast breakage index for estimating ballast breakage is introduced.

2 METHODOLOGY

Railway ballast obtained from a local WA quarry with a size between 4.75 and 53 mm was used in this study.

2.1 DIGITAL IMAGING IN LABORATORY TESTING

The laboratory system and setup of the digital image processing used in the current study is similar to that of Kwan et al. (1999). A schematic diagram of the system is shown in Figure 1, and consists of a sample tray, a photographic stand fitted with light resources, a high resolution digital camera and a computer with image analysis software.

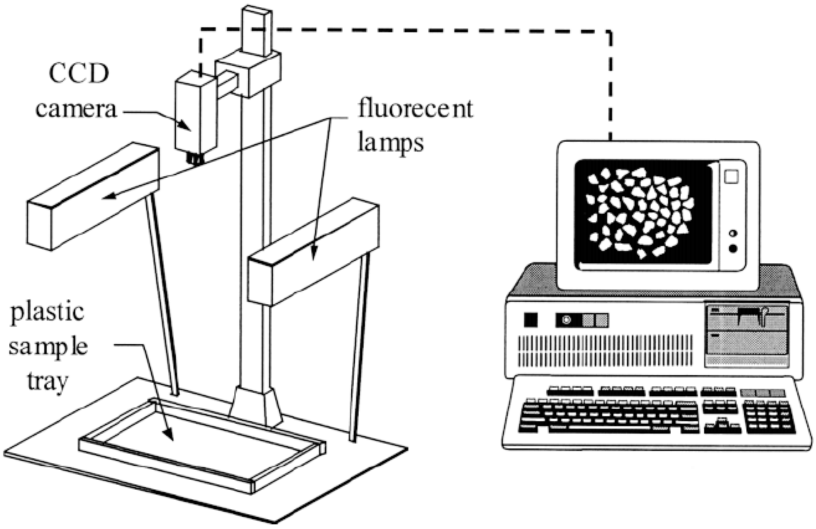

Figure 1: Laboratory digital imaging system and setup (Kwan et al. 1999)

The digital image processing starts with laying a coloured card on the sample tray and adding 16 kg of fresh ballast onto the sample tray. The ballast particles are arranged manually in such a way that they are not touching, overlapping or falling outside the boundary of the measurement area. Top and back lights (with light diffusers to reduce the shadow effect) are applied and images are captured using the digital camera and stored in the computer for the image analysis. The captured images are processed using the free access software package ImageJ (Ferreira and Rasband 2011). The following steps are used to process the captured images. The image scale is set and unnecessary parts are cropped. The image is turned to black and white, and the threshold is changed so that the entire sample is represented in the analysis. The image is converted into binary, eroded (i.e. removing pixels from edge of black objects) and dilated (i.e. adding pixels to the edge of black particles). The particles are then analysed by measuring their length, breadth and area, and the measurement results are saved in an Excel file for the image analysis calculations. In general, the image analysis measures 2D images and its accuracy is dependent on the quality of the captured images. In order to take high quality pictures, the height of the video camera is adjusted to obtain a sufficient measurement area of the sample tray, and lights are also adjusted to reduce the shadow effect. Typical example of a captured image and its binary version are shown in Figure 2.

Captured **Binary**

Figure 2: Typical example of a captured image and its binary version in the image analysis

A number of experiments were carried out to investigate the effects of some factors affecting the digital image processing and the most effective setup was used for the rest of testing. The factors investigated included the particle shape, colour of card and particle touching. In order to investigate these factors, the image analysis was compared with sieve analysis from the mechanical sieving. Sieve analysis is currently the most widely used method to determine the particle size distribution, yet not convenient for estimating ballast breakage in the field. The sieve analysis was carried out in accordance with the Australian Standard (AS 1289.3.6.1). The mechanical sieving was performed by placing the ballast sample on a set of sieves of different sizes (i.e. 53, 37.5, 26.5, 19, 13.2, 9.5 and 4.75 mm) and the sieves were mechanically shaken for 15 minutes. During the shaking, the particles pass through the sieves of smaller sizes, while retained on the sieves of sizes too small for them to pass through. However, after the shaking is done, not all retained particles on a sieve are actually larger than the sieve apertures. Particles slightly smaller than the aperture size sometimes get stuck without passing through the sieve. Therefore, manual checking and hand sieving was required to make sure that all particles retained on a sieve are bigger than the sieve apertures. After the sieving, the mass retained on each sieve was measured and used for gradation.

As explained above, the sieve analysis is based on the mass retained on each sieve (i.e. mass gradation) whilst the image analysis is an area gradation. Therefore, some discrepancy between the sieve analysis and image analysis is expected. This discrepancy is calculated by averaging the difference at D_{20}, D_{50} and D_{80} of the gradation curves determined by the image analysis and sieve analysis using the following equation (e is the discrepancy):

$$e = \left(\frac{D_{n-IA} - D_{n-SA}}{D_{n-SA}} \right) \times 100 \tag{1}$$

where: $D_{n\text{-}IA}$ and $D_{n\text{-}SA}$ are the particle sizes corresponding to n % passing from the image analysis and sieve analysis, respectively, and n = 20, 50 and 80%.

2.2 DIGITAL IMAGING IN FIELD CONDITIONS

One of the disadvantages of sieve analysis is its difficulty to be applied in the field as it is a laboratory test. In this sense, the image analysis is more attractive and beneficial as it can be applied in-situ. In order to replicate the field conditions, outdoor digital imaging experiments were carried out using 16 kg of fresh ballast. The experiments were conducted under the sun without electrical lights, and the results were compared with those obtained from the laboratory sieve analysis to examine the feasibility of using the digital imaging technique in the field.

2.3 BALLAST BREAKAGE INDEX

On successful completion of the image analysis for fresh ballast, the ballast was degraded using the Los Angeles machine so as to obtain degraded ballast similar to that of underneath the sleepers. The Los Angeles test was conducted according to the Australian Standards (AS 1141.22) for 1100 turns. The fines in the sample were removed as they do not ultimately contribute to the integrity of the ballast. The image analysis was then performed on the degraded ballast and the gradation curves obtained from the image analysis of the fresh and degraded samples are used to determine the ballast breakage.

As mentioned earlier, the determination of ballast breakage due to induced train loading is important for maintenance cycles. Various particle breakage indices have been proposed in the literature to quantify the degree of particle breakage in granular materials. However, most available methods are based on the increase in the percentage passing a single sieve size. Lackenby (2006) proposed a more successful breakage index for ballast based on the changes to the entire particle size distribution. This breakage index uses the areas A and B between the boundaries of fresh and degraded size distribution curves and an arbitrary boundary of maximum breakage, identified to be the line passing through the smallest sieve size 2.36 mm and D_{95} (or d_{95}) of the largest sieve size (see Figure 3). The ballast breakage index (BBI) can then be calculated as follows:

$$BBI = \frac{A}{A+B} \tag{2}$$

If it happens that the value of D_{95} leads the boundary line to intersect with the particle size distribution curve, the D_{85} (or d_{85}) can then be tried. The shift in the distribution curve traces out the area A, and area B is the potential breakage or the area between the arbitrary boundary of maximum breakage and the final particle size distribution. The lower the breakage the smaller the shift in the gradation curve from its original position, thus, the closer the value of A to zero and consequently the closer the BBI to zero.

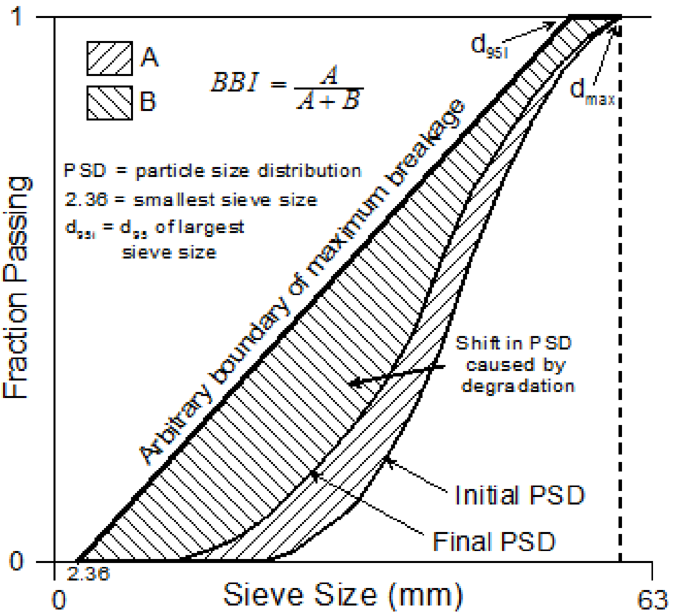

Figure 3: Explanation of the ballast breakage index by Lackenby (2006)

The definition of the boundary line explained by Lackenby (2006) is based on the largest sieve size in the *x-axis* of the gradation curve, which may change depending on the geometry and position of the particle size distribution from the boundary line (e.g. d_{95} may or may not be suitable and if not, d_{85} should be tried). This may lead to inconsistent *BBI* depending on whether d_{95} or d_{85} is used. In the current study, a modified boundary line is proposed which is believed to be more reliable and consistent. The proposed boundary line connects the origin of the grain size distribution curve with a point obtained from the 90% passing in the *y-axis*, as shown in Figure 4. This method leads to consistent *BBI* as it takes into account the changes in the largest particle size without the need to change its definition for any particular grain size distribution curve.

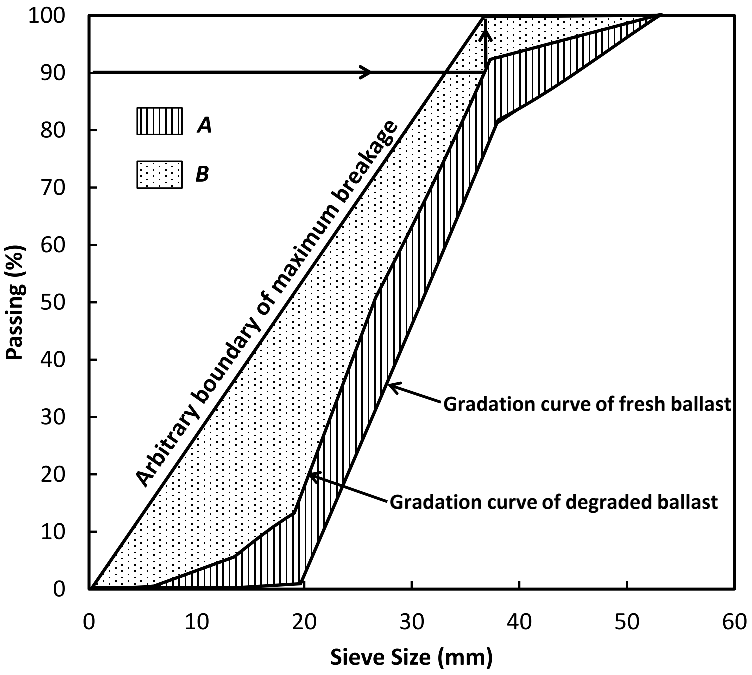

Figure 4: Explanation of the modified ballast breakage index

3 RESULTS AND DISCUSSION

Each factor affecting the image analysis was investigated by comparing the final image analysis results with the results of the final sieve analysis. These factors include the modelled particle shape, colour of card and particle touching or overlapping. The tests are initially carried out using a white card paper and the particles are not allowed to touch and overlap.

The particle shape was modelled by three different fitting areas: ellipse, rectangle and circle, and the results are given numerically in Table 1 and shown graphically in Figure 5. It can be seen that the ellipse shape provides the least gradation difference (16%) between the image analysis and sieve analysis. Based on these results, it was decided to use the fitted ellipse for the rest of experiments.

Table 1: Effect of particle shape on the image analysis

Fitted shape	Discrepancy between the image analysis and sieve analysis (%)
Ellipse	16
Rectangle	30
Circle	77

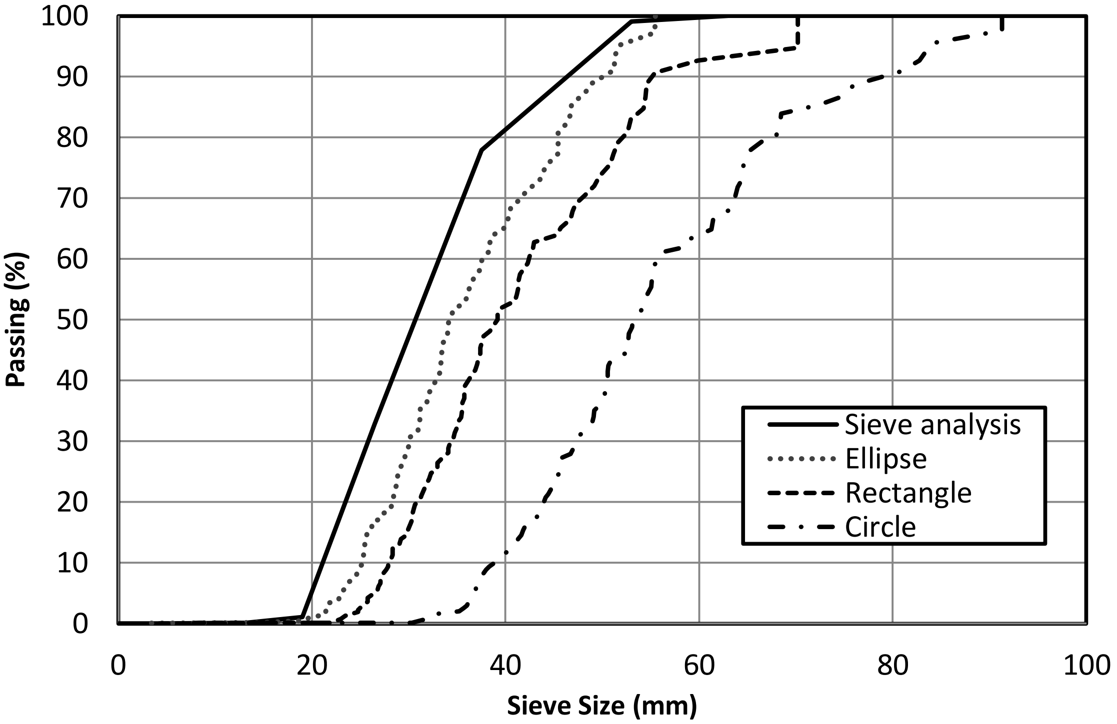

Figure 5: Effect of particle shape on the image analysis

The image analysis was tested against three different card colours: white, black, and transparent white, and results are given in Table 2 and shown in Figure 6. It can be seen that the transparent white card paper provides the least difference (8%) between the image analysis and sieve analysis.

Table 2: Effect of card paper colour on the image analysis

Card paper colour	Discrepancy between the image analysis and sieve analysis (%)
White	11
Black	10
Transparent white	8

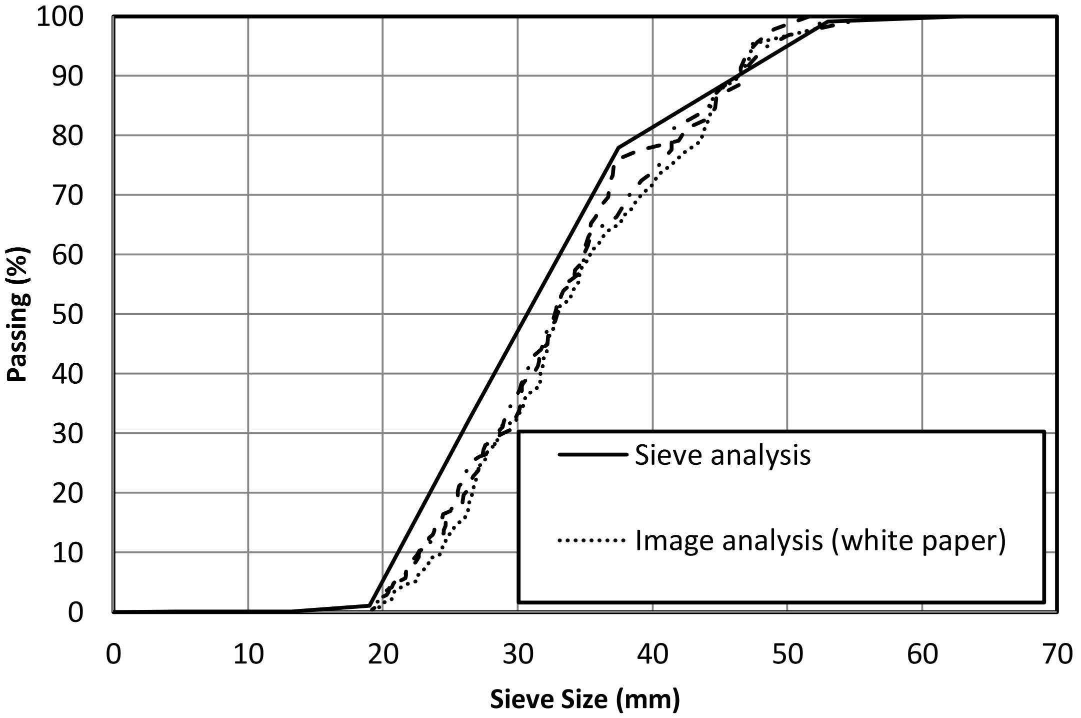

Figure 6: Effect of card colour on the image analysis

In previous studies of image analysis found in the literature, the particles were not allowed to contact each other while images are captured. In this study, a trial was made in which particles were allowed to contact to each other or overlap, and the built-in function "watershed" available in the ImageJ software was used to conduct the image analysis. This function separates or cuts the touching particles and can thus deal with captured images of touched or overlapped particles. Figure 7 shows the results of the image analysis obtained from experiments conducted on both touching and non-touching particles. It can be seen that the "watershed" function can effectively analyse the touching particles in the image analysis. The difference in the image analysis between the touching and non-touching particles is found to be 3%. This accuracy is an advantage as it reduces the time and effort needed for separating the particles.

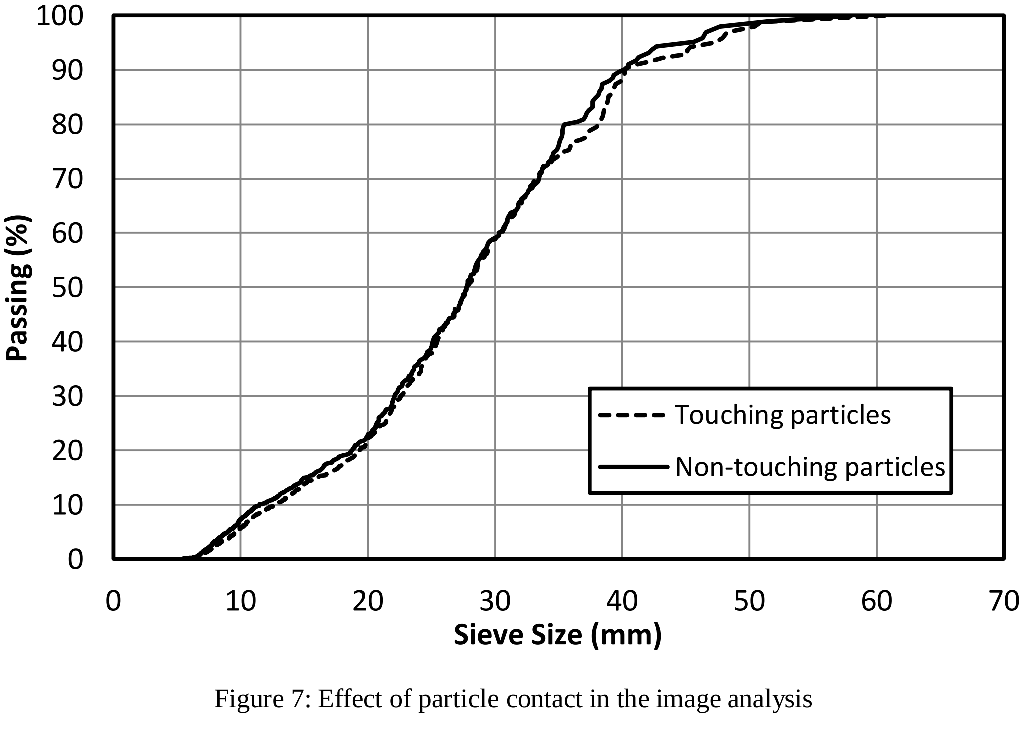

Figure 7: Effect of particle contact in the image analysis

The results of the outdoor testing that replicates the field conditions are shown in Figure 8. It can be seen that good agreement is obtained between the laboratory sieve analysis and field image analysis, with a small difference of 3%.

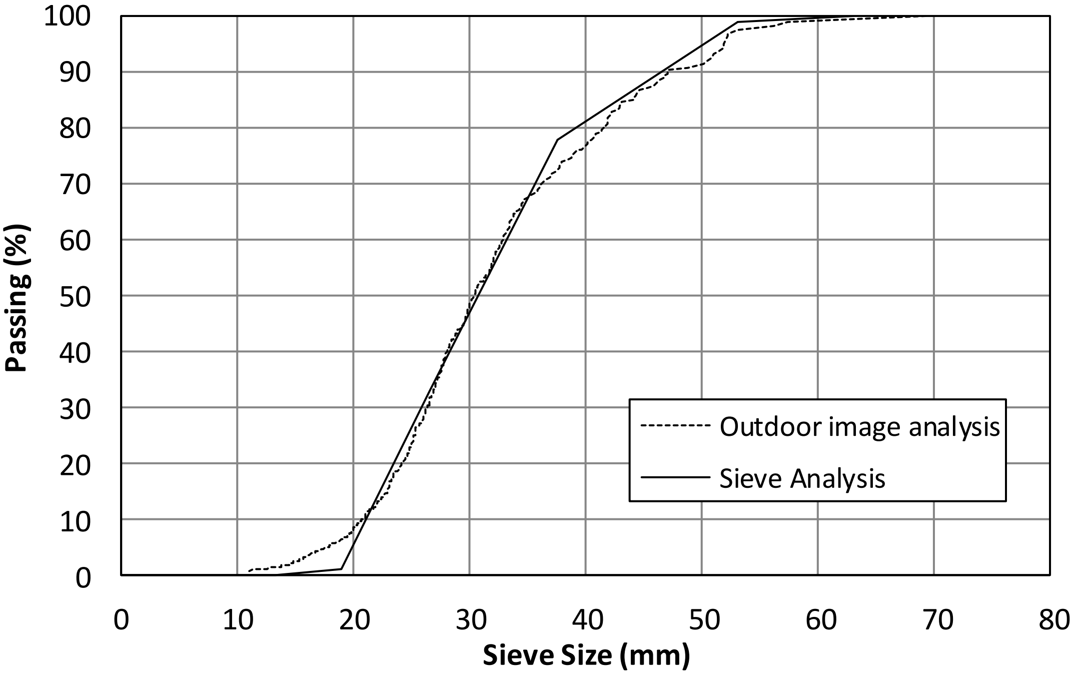

Figure 8: Comparison between the sieve analysis and (field) image analysis

Using the modified breakage ballast index developed in the current study, the *BBI* for the image analysis was found to be 0.36, whilst the sieve analysis returned *BBI* of 0.33, leading to a difference between the sieve analysis and image analysis of 9%. This is acceptable given the fact that the sieve analysis in not the most reliable test and it uses the mass retained at a sieve, whilst the image analysis relies on particle dimensions and area. The "geometric model" PSD curves and the actual PSD curves used for calculations of the *BBI* for the sieve analysis and image analysis are shown in Figures 9 and 10, respectively.

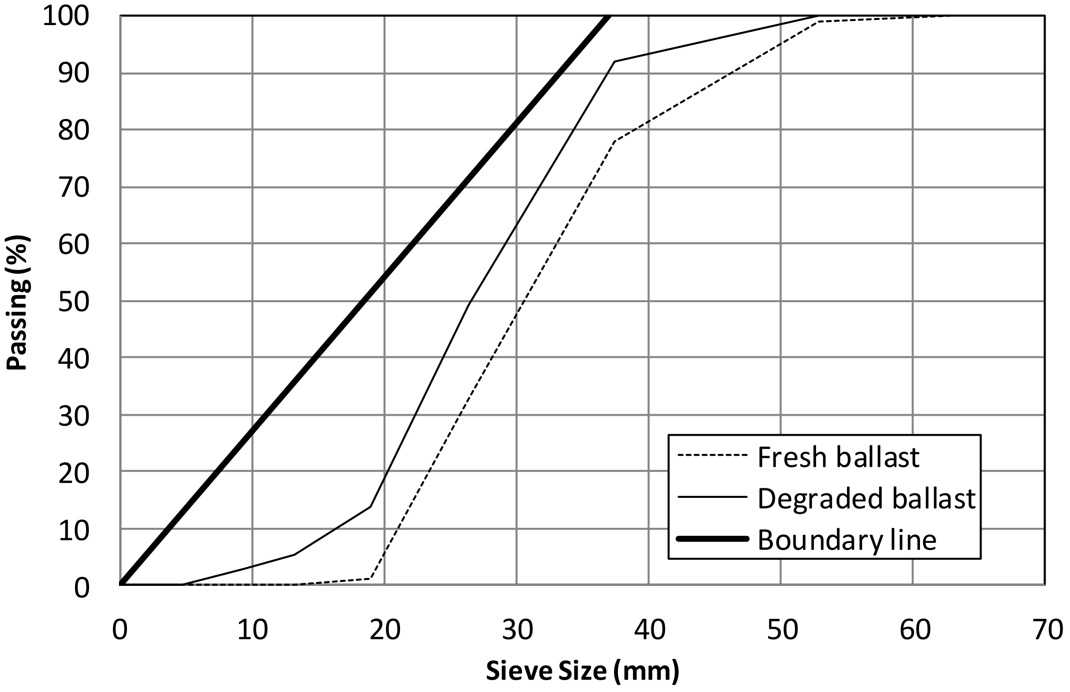

Figure 9: Sieve analysis gradation curves used for calculation of *BBI*

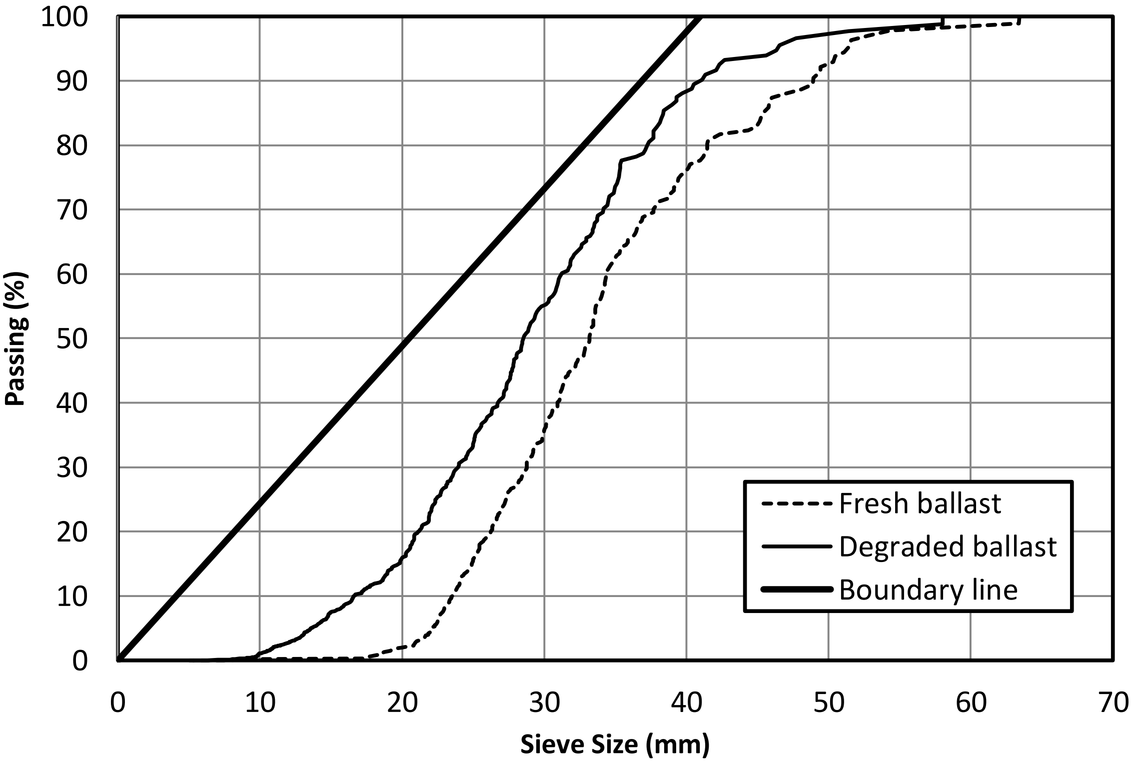

Figure 10: Image analysis gradation curves used for calculation of *BBI*

4 CONCLUSIONS

The feasibility of using the digital imaging technique for ballast gradation and breakage estimation was investigated and based on the results obtained, the following observations were made:

- The image analysis from the digital imaging technique can be used successfully in the laboratory and in the field, and its results agree well with those obtained from sieve analysis
- The digital image processing is more effective when the particle shape is modelled as an ellipse and when white transparent card is used.
- The digital imaging technique yields more information about ballast than the mechanical sieving such as the particle angularity and elongation, which contribute to the ballast strength and stability.
- Given the fact that the ballast samples used in the image analysis are not affected by the moisture content, there is no need to dry the sample, which means that the image analysis is more time-efficient than the sieve analysis. In fact the image analysis can be completed in about 10-15 minutes, whereas 1 to 2 hours are usually required for the sieve analysis.
- The image analysis obtained from the outdoor testing under the sun light gives good representation of the sieve analysis. Hence, the image analysis can be used in the field for estimation of the ballast breakage. Engineers are now able to get results almost immediately without having to send the ballast samples to the laboratory and without having to rely on the visual inspection alone. The overall results indicate that the image analysis can be used in the field with success, and has the potential for future development.

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