AN INVESTIGATION OF AGGREGATE DEGRADATION IN A HIGH STRESS FIELD

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ABSTRACT

The deterioration of the aggregate material used in road construction is of concern as it affects the overall long term stability of the road pavement and should be minimised by using durable aggregates. The paper presents proof of concept of an experimental system, developed to assist in the evaluation of aggregate quality, using a customised rolling model drum, in which the aggregate assemblage is subjected to different stress levels by using the geotechnical centrifuge modelling technique. The outcome of the study has demonstrated the operation and functionality of the system and the potential to quantify aggregate durability solely dominated by particle-to-particle interaction mechanism.

1. INTRODUCTION

The basic functional operation of a road is to provide better accessibility, connectivity and mobility between centres, for the transportation of people and goods during its service life. The functional operation of the road will be affected by among others, the quality of materials within the road prism. Depending on the state of density and stresses, grain crushing under laboratory testing has shown to reduce the resilient modulus of the aggregate material by half and permanent deformations increase up to three times more (Zeghal, 2009). The long-term performance of rail tracks is affected by particle breakage which alters the size and shape of ballast aggregates (Sun and Zheng, 2017). It is therefore essential that the aggregate material and any other materials for that matter, used in the pavement layers, should be durable and their deterioration should be minimal (Paige-Green, 2007). As the aggregate particle-to-particle interaction play an important role in the aggregate degradation and therefore stability of the pavement structural layers, special attention is therefore given to durability of the materials, particularly in the upper structural layers.

There are several commonly used test methods to determine the suitability of rock aggregates for use in pavements and they provide a better understanding of the quality of aggregates. However, the quality of the aggregate is influenced by a number of factors, including microstructure, grain size, shape of rock forming mineralogy (Sousa et al. 2005; Cuelho et al., 2008; Tavares and das Neves, 2011; Sengoz et al., 2014), petrology (Anastasio et al., 2017) and presence of deleterious clays (Paige-Green, 2007). The quality and therefore durability of rock materials can also vary significantly within a quarry (Leyland et al. 2013). Based on reported studies by several authors on aggregate quality evaluation methods (Sampson and Netterberg, 1989; Paige-Green, 2007; Cuelho et al., 2008; Erichsen et al., 2011; Leyland et al., 2013; Leyland et al., 2015; Liu et al., 2017), the different test methods can be classified as either being physical and mechanical or chemical tests in nature. The tests use different mechanisms to quantify the relative durability of the aggregate sample. In the physical and mechanical test methods, resistance to crushing and abrasion is measured, while in chemical tests, resistance to disintegration is commonly measured through aggregate sample saturation in solution, for example Ethylene Glycol (Leyland et al., 2015) Sodium Sulfate Soundness tests (Sousa et al. 2005; Liu et al, 2017).

The choice of the method or a combination of the test methods for durability evaluation depends on the required parameters to meet material specifications for pavement design and the type of rock (Weinert, 1984; Netterberg, 1994; Paige-Green, 2007). As aggregate particle-to-particle interaction will play an important role in the stability of granular pavement structural layers, an understanding of the rate of aggregate degradation due to particle-to-particle interaction as a result of applied stresses is essential. The test methods to evaluate the durability or quality of aggregates involving some form of particle to particle interaction under load are mostly the mechanical tests (Paige-Green, 2007; Lui, 2017), include the L.A abrasion (LAA), Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Durability Mill Index (DMI), Aggregate Durability Index (ADI) and the 10% Fines Aggregate Crushing Value (10% FACT) and the Micro-Deval (MDE).

In the existing abrasion tests, a charge of steel balls is used to induce aggregate wear, for example in the MDE test, and impact and grinding, as is the case in the LA test, in which the interior of the drum is mounted with a shelf which picks up and drops the aggregates and the steel balls as the drum rotates. The particles are thus subjected to external force, resulting in the particle degradation. The overall objective of this study is to generate knowledge in aggregate degradation that is solely dominated by particle-to-particle interaction mechanism, without the use of steel balls.

The focus of the paper is to present the proof of concept of the experimental system, developed to assist in the evaluation of aggregate quality, using a customised rolling model drum, in which the aggregate assemblage is subjected to different stress levels. An innovative approach is explored, in that the experimental system consists of rolling an aggregate assemblage in a rotating model drum, in a high acceleration field, by testing in the geotechnical centrifuge. Scaling laws applicable to geotechnical centrifuge modelling are used to determine the relationship of the magnitude of the induced forces or stresses between the model and the prototype (Schofield, 1980; Garnier et.,2007). The scaling laws, used for the centrifuge test between small-scale model and full-size prototype, applicable for this study are listed in Table 1.

Table 1: Centrifuge scaling laws

Quantity	Scaling factor (prototype/model)
Acceleration, gravity	1/N
Density (ρ)	1
Displacement	N
Force	N^2
Length	N
Mass	N^3
Stress (σ)	1
Strain	1
Time (dynamic)	N
Volume	N^3

During geotechnical centrifuge testing, the model drum is spun around the central axis at a high rotational speed, and from the scaling laws in Table 1, with regard to force, thereby increasing the body forces acting on the aggregates. The assemblage is therefore subjected to external forces, that are imposed by the increased self-weight of the aggregate particles due to increased gravitational forces as a result of testing in the high acceleration field.

Since the magnitude of the induced, normal contact and tangential forces, between the particles are a result of the g-level during the testing, the rate of aggregate degradation or wear due to abrasion, should therefore be related to the g-level. In using the geotechnical centrifuge modelling technique and due to the increased self-weight of the particles, it should be possible to test without the use of the charge of steel balls in the model drum to induce impact and abrasion. This will be possible if the behaviour of the mass of the particles in the model drum is further dominated by cascading and cataracting behaviour as defined by Morrison et al (2016). The degradation is then assumed to be driven by sliding and impacts and should manifest itself through a gradual reduction of the size of the particles and generation of fragments and fines, due to fragmentation and abrasion that involves multi-particle-to-particle abrasion process. Characterisation of the effect of stress level on the rate of degradation can be done by quantifying changes to particle form and generated amount of fines.

The aggregate particle form has been found to be affected by the production process. For example, the experimental study reported by Bouquety et al (2007), showed that feed grading during crushing, different spreading of feed fractions, have a significant influence on aggregate flakinesss, shape of global size fractions. Regardless of the aggregate type, a clear distinction of product angularity value has been observed between the crushers, indicating that the aggregate crushed with impact crusher exhibits the highest angularity value whereas roll crusher displays the lowest angularity value (Sengoz, et. al (2014). Mgangira et al (2016) found a statistically significant difference, between four different crusher types, for all the aggregate shape parameters that were examined. However, sphericity values were the most successful in identifying differences between the crusher types, which included: Jaw crusher, Osborn 57H Cone crusher, 4 1/4 Cone crusher and Barmac crusher. It should therefore be expected that the mobility of the aggregate particles and therefore the particle-to-particle interaction during rolling in the model drum, will be affected by the aggregate shape characteristics, influenced by the crusher type. The determined changes in aggregate shape characteristics or amount of generated fines, should be consistent with expected results of the influence of stress level, for the testing system, which is solely based on particle-to-particle interaction mechanism, to demonstrate that it can provide a better understanding of aggregate degradation behaviour.

2. EXPERIMENTAL

Test equipment

An aggregate abrasion test device (AATD) was used to quantify the aggregate degradation. The AADT, in-house built by the Mechatronics Group of the CSIR, is a motor driven model drum, shown in Figure 1. The complete testing system is shown in Figure 1, consisting of: computers (in the control room), used for controlling test conditions and monitoring; the geotechnical centrifuge; a variable frequency drive (VFD) and the AATD. The model drum is rotated to a desired rotational speed by the use of the VFD. The University of Pretoria geotechnical centrifuge is classified as a 150 G-ton instrument. It is thus, capable of accelerating a model weighing up to 1 ton, to 150 times the earth's gravity. The centrifuge model platform measures 0,9 m x 0,8 m with unobstructed headroom of 1,3 m. The radius, measured from the centrifuge axis to the model platform, is 3 m.

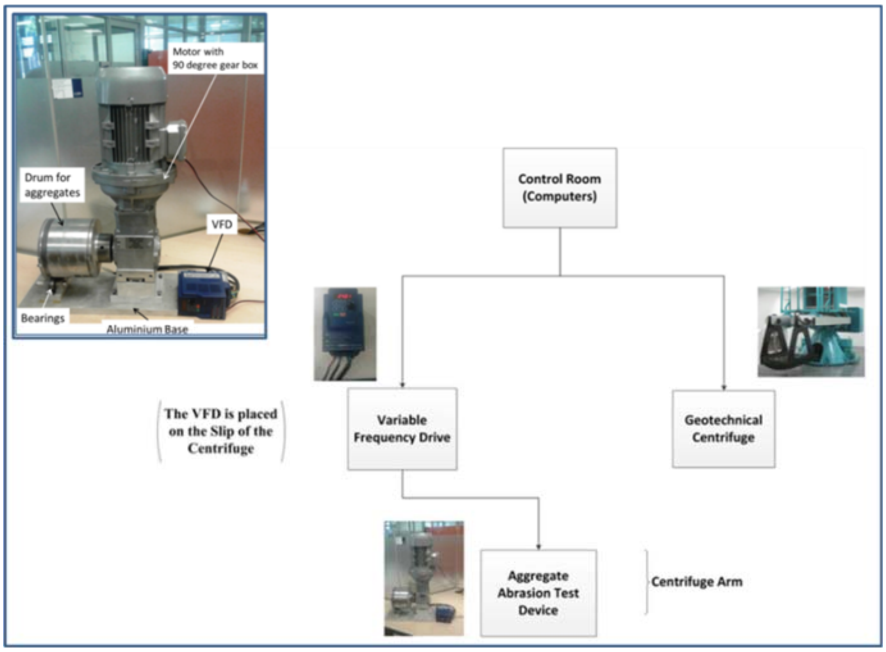

Figure 1: Schematic layout of the aggregate abrasion testing system

Material

The material used in the test was a quartzite aggregate, sourced from Afrisam Ferro Quarry in South Africa, also used in the study by Mgangira et al (2016). As a proof of concept stage, only a single particle size range was used in each test rather than a mixture of different size particles. A representative aggregate sample of material passing the 26.5 mm sieve but retained on 19 mm sieve, was obtained for the different crusher type. This size range of fraction is considered as an intermediate test fraction for road and railway application. 30 randomly selected particles created the two sub-samples from each crusher type.

Test procedure

The total mass of the aggregate sample was determined before being loaded into the model drum. The AATD was then mounted on the centrifuge model platform. During geotechnical centrifuge testing, the model drum is spun around the central axis at a high rotational speed, thereby increasing the body forces acting on the aggregates. Thus no steel charge was used in the experiment to induce the impacts. The centrifuge's acceleration was increased to a desired gravitational acceleration, controlled by using one of the computers from the control room, before each of the abrasion test could begin. Once the desired acceleration was reached and stabilised, the model drum was rotated at a rotational speed of 100 rev/min in all the tests. The abrasion tests were run at centrifuge acceleration of 10g and 20g, for a period of 5 minutes in both cases, which according to the scaling laws represents 50 and 100 minutes respectively, in a dynamic test environment. Samples from each crusher type were subjected to the same test conditions.

At the end of each test, the material was carefully removed from the drum and weighed before sieving on the 2 mm and 0.075 mm sieves, to determine the degradation value and fines generated. The particles were then washed and oven dried before analysing them using the three-dimensional (3D) laser scanner, to determine the changes in aggregate shape characteristics.

3. RESULTS AND DISCUSSION

The results of the abrasion test for the different samples tested at centrifuge acceleration of 10g and 20g are presented and discussed below. It should again be emphasised that the testing at this stage, is not simulating a specific event requirement, but to demonstrate functionality of the system and its potential to quantify aggregate resistance to abrasion and therefore durability, solely dominated by particle-to-particle interaction mechanism using a model drum. The results are presented in terms of change in aggregate shape, aggregate degradation value and amount of generated fines as a result of stress levels.

Change in sphericity

The 3D sphericity of the particles, defined according to Eq. 1 (Wadell, 1935), takes into account the particle volume (V) and particle surface area (SA), which are directly calculated from the 3D laser processed data.

$$S_{3D} = \sqrt[3]{\frac{36\pi V^2}{SA}} \quad \text{Eq. 1}$$

The expectation is that as the particles make repeated contacts with each other during the course of test as a result of the rolling and tumbling in the model drum, the particles should become more regular and the sphericity should increase. The results in Figures 2 and 3 show variation of the sphericity distribution plots for the original material (red), after testing at 10g (green) and 20g (blue) for the different crushers. All the results show a clear relative increase in the sphericity for the material tested at 10g and 20g compared to the original material as reflected by the relative positions of the distribution plots. The results indicate that the testing of the aggregates at different acceleration levels, led to increasing sphericity values, compared with the original sample. It is evident that shape change at 20g is higher than that at 10g, showing the influence of increased selfweight of the aggregates.

The Jaw crusher results significantly show the influence of the centrifuge acceleration level as reflected by a further shift to the right in the distribution plot of the 20g results, relative to the 10g results. In other words severity of the particle-to-particle abrasion mechanism increased with increase in acceleration level, illustrating variation of the aggregate shape extent with acceleration level. The results of the other crusher types show a slight difference in the sphericity distribution plots between 10g and 20g.

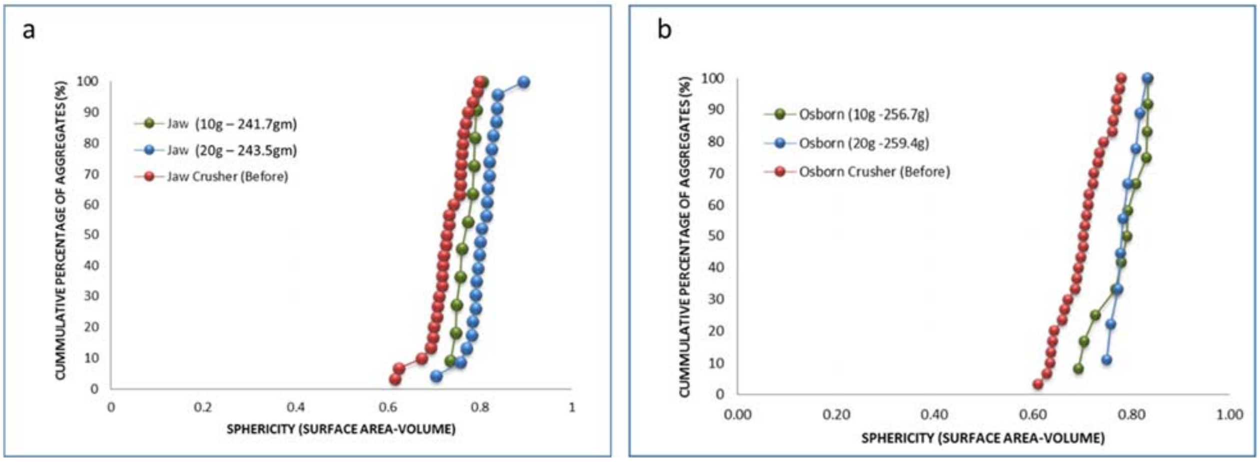

Figure 2: Variation of aggregate sphericity for: (a) Jaw crusher and (b) Osborn crusher

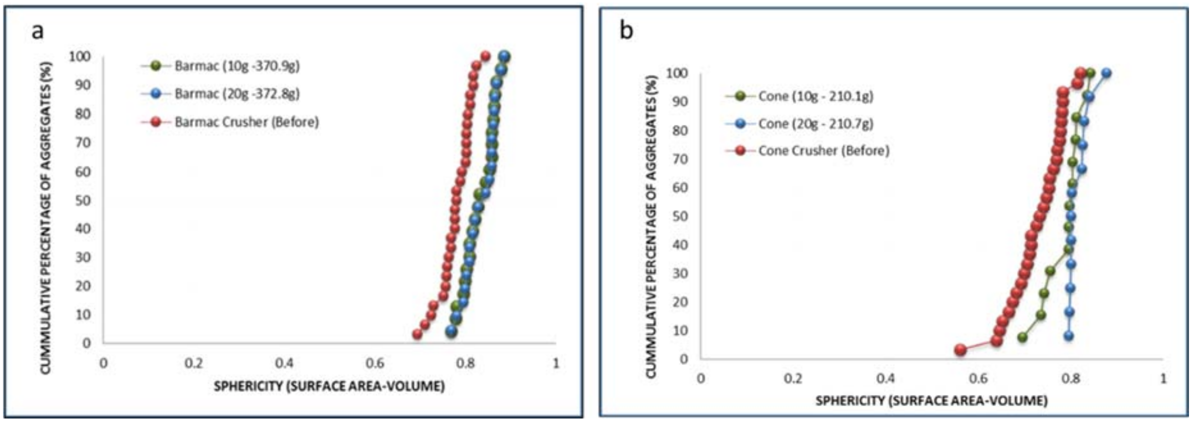

Figure 3: Variation of aggregate sphericity variation for: (a) Barmac crusher and (b) Cone crusher

While this is an initial study, the results suggest that the wear due to particle-to-particle abrasion mechanism is to an extent influenced by the variation of initial particle shape which is also influenced by the production process (Bouquety et al., 2007) The results are also consistent with the observations made by Diógenes et al (2018) who point out that crushing processes have inherent differences that can influence the product shape properties, despite the types of crushers used being generally the same.

Degradation value and fines generation

The degradation value was determined as a mass loss of the sample through a 2 mm sieve per mass of the initial particle assemblage and generated fines was determined as the mass passing the 0.075 mm sieve. The amount of the generated fines was normalised to the initial mass of the aggregate assemblage and expressed as mg/g. Figures 4 and 5 show the degradation values and the generated fines proportions under the same drum rotation speed of 100 revolutions per minute. It can be seen that increasing the test acceleration level led to increasing degradation values and increase in the generated fines, showing the influence of increased selfweight as should be expected. As was observed in the results presented on the sphericity, the extent of the degradation and the generated fines are different from the different crusher types.

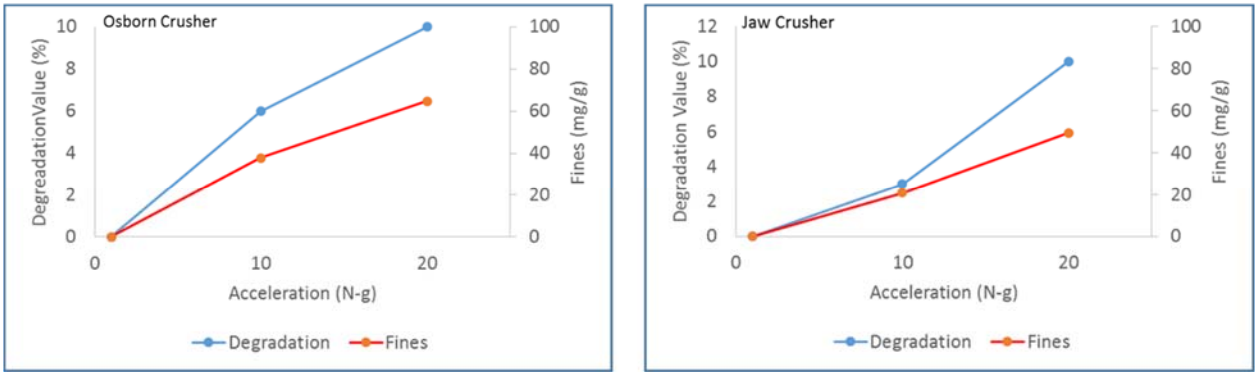

Figure 4: The Degradation Value and generated fines proportion at different centrifuge acceleration levels

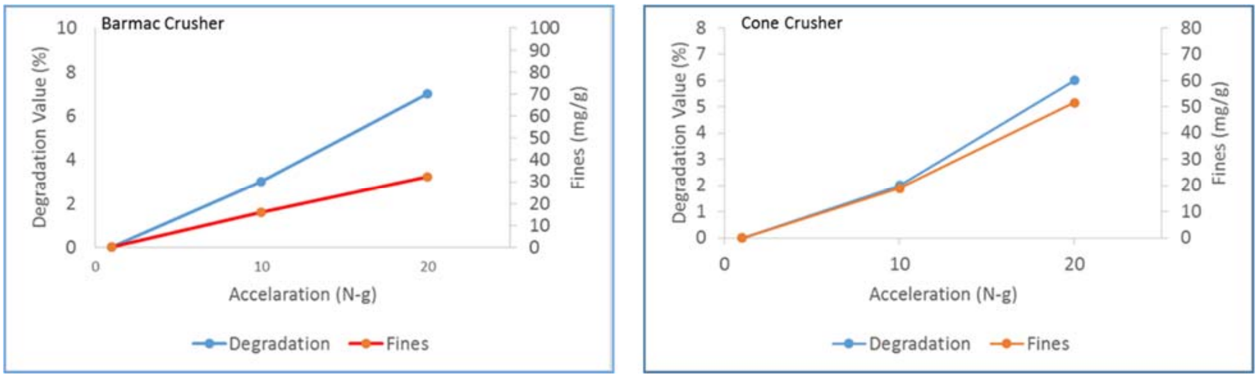

Figure 5: The Degradation Value and generated fines proportion at different centrifuge acceleration levels

The study is continuing, aimed at exploring the quantification of the effect of stress level conditions on changes in the aggregate particle size and shape distribution and therefore durability, on the assumption that both abrasion and mechanical fragmentation are potentially dominant aggregate particle degradation mechanisms, created in a small model drum as a result of simulated increased gravitational forces, by conducting the test in the centrifuge. No actual event or test method was being simulated in the presented study, but has validity as it is the knowledge of active degradation taking place in the test method that is being aimed at, rather than the understanding of the real breakdown of the aggregates (Erichsen et al., 2011).

There are a number of research questions to be investigated, including scaling laws for flow rate in the model drum as it is influenced by the geometrical parameters between the drum diameter and the particle diameter as well as the drum width and particle diameter (Govender 2016). This will include effect of the pay-load in the model drum during the testing. The testing of mixtures of various particle sizes, with the ultimate goal of modelling changes in the mean particle diameter in such mixtures, as well as investigations on the influence of wet and dry test conditions and different types of rock samples, will form part of the future test programme.

4. CONCLUSIONS

The presented experimental platform has demonstrated the possibility of quantifying aggregate degradation values using a testing system, consisting of small scale model drum in a centrifugal acceleration field, in which the observed particle abrasive attrition or fragmentation will solely be due to particle-to-particle interaction. The effect of stress level on aggregate abrasion/wear is demonstrated through the quantification of fines generated and changes in the aggregate shape characteristics following rolling of the samples in the model drum. The results of the amount of generated fines and changes in the aggregate shape characteristics are consistent with expected influence of stress level. The outcome of the study has demonstrated the operational and functionality of the system and testing platform and its potential to quantify aggregate durability, solely dominated by particle-to-particle interaction mechanism.

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