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Gyratory abrasion with 2D image analysis test method for evaluation of mechanical degradation and changes in morphology and shear strength of compacted granular materials

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HIGHLIGHTS

- GAIA test was used to evaluate degradation, morphology, and strength of aggregates.
- Shortcomings of the LA abrasion test were revealed by comparing to GAIA test.
- The effect of energy levels on materials' compaction characteristics was evaluated.
- Performance-based compaction specifications can be set using the GAIA test result.

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ABSTRACT

Mechanical degradation of granular materials can significantly influence the performance and durability of pavement systems. The commonly used Los Angeles (LA) abrasion test does not test the entire gradation of the material, nor simulate the compaction and field loading conditions. A new Gyratory Abrasion and Image Analysis (GAIA) test method was developed in this study and compared with the LA abrasion test for five granular material types. Results show that the GAIA test can address shortcomings of the conventional test, provide insight into mechanical behavior of granular materials during compaction, and enable performance-based specifications for field compaction of granular materials.

1. Introduction

Mechanical degradation or abrasion of granular materials used for unpaved road surface and pavement base layers can significantly influence their mechanical properties, drainage conditions, and freeze-thaw durability [1–4]. As detailed in several previous studies, the degradation and abrasion of a granular material is a function of its mineral composition, gradation, morphology, and loading conditions including compaction during construction and traffic loading over the service life of a roadway [4–10]. Previous studies have illustrated the effects of gradation and loading conditions on the degradation of aggregate, railroad ballast, and soils using static or cyclic triaxial tests [4,10–12]. To more practically evaluate degradation characteristics or create specifications for granular materials, most researchers and transportation agencies

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rely on the Los Angeles (LA) abrasion and Micro-Deval tests, which require specimens to be prepared to standard gradings and tested in a rotating steel drum containing steel spheres [13–15]. However, these two testing methods do not simulate the actual loading conditions responsible for the degradation and performance of the materials, and do not test their full gradations.

To address these deficiencies, a new laboratory testing method is proposed and developed herein, which employs the gyratory compaction device and two-dimensional (2D) image analyses to evaluate the mechanical degradation and changes in morphology and shear strength of granular materials under simulated field compaction loads. The new method, termed the Gyratory Abrasion and Image Analysis (GAIA) method, aims to more accurately predict the actual degradation of granular materials after compaction, and rapidly establish the density-strength-compaction energy relationship for a material. The latter can be used to develop performance-based specifications that ensure field performance, minimize material degradation, and save time and energy. This paper details the new testing method and associated analyses, compares the results with those of conventional LA abrasion tests using five types of granular materials, explains the behavior of the granular materials during the gyratory compaction tests, and demonstrates how the test results can be used to develop performance-based specifications for field compaction of granular materials.

2. Background

The following sections provide background information on the mechanical degradation of granular materials as well as details on the gyratory compaction and image analysis techniques used for quantifying particle morphology in this study.

2.1. Gradation and loading effects on mechanical degradation

Mechanical degradation of granular materials can significantly decrease resilient modulus by up to 50% and increase permanent deformations by 100%–300%, resulting in significant rutting and cracking on roadway surfaces [8]. It is widely known that uniformly graded or gap-graded aggregates can experience significantly more degradation than well-graded aggregates, because the lower void ratio of well-graded materials results in lower inter-particle contact stresses. As a result, well-graded materials tend to break down more slowly than uniformly graded materials under a given set of loading conditions [4–5,16]. For example, the effects of maximum particle size and coefficient of uniformity (C_u) on the permanent deformation and degradation of railroad ballast were examined using large-scale cyclic triaxial tests [17], and it was reported that particle breakage was significantly reduced when C_u was larger than 1.8. Particle breakage is also significantly influenced by load duration, with reported values of breakage index under creep loading being more than 1.5 times those of monotonic loading [12]. Based on results of cyclic triaxial tests, degradation can also be minimized by keeping the confining pressure within a certain range [18].

2.2. Gyratory compaction device and pressure distribution analyzer

The gyratory compaction test was originally developed for mix design and field management of hot-mix asphalt (HMA) mixtures [19]. In this test, two compaction mechanisms: a constant vertical pressure and gyratory shear stresses induced by eccentric loadings are used to simulate field compaction and traffic loads [20–21]. Previous studies have demonstrated that the gyratory compactor is also useful for evaluating the compaction characteristics of soils ranging from coarse aggregates to high-plasticity clays [22–24]. The effects of the four equipment operational parameters, which are the vertically applied pressure and the angle, frequency, and number of gyrations, have been well studied for both HMA and soils [25–26]. Compared to other laboratory compaction methods such as impact and vibratory compaction, it has been reported that the gyratory compaction curves for soils can better replicate field compaction results [27].

A pressure distribution analyzer (PDA) was also developed in a prior study to monitor changes in shear resistance of HMA specimens during gyratory compaction [28]. The PDA uses three load cells to measure the applied vertical load and changes in eccentricity of the load during the test. Based on the PDA data and equipment operational parameters, the theoretical compaction energy applied to the specimen can also be calculated [20]. The repeatability of using the PDA to measure shear resistance of a granular material (Ottawa sand) was reported to be less than 7 kPa, and a strong linear correlation ($R^2 = 0.89$) was found between the PDA-measured shear resistance and unconfined compressive strength for a fine-grained granular material possessing some apparent cohesion [22].

2.3. Particle morphology and image analysis techniques

Aggregate morphology has long been recognized as an important factor affecting the engineering properties and degradation of granular materials [1,29,30]. Various parameters proposed to quantify the external morphology of particles can be categorized in a three-tiered hierarchy of observational scales with respect to particle size: form, angularity, and surface texture [31–33]. The Rittenhouse and Krumbein charts were conventionally used to visually classify the sphericity and roundness of particles, respectively [34–35]. As development of imaging and computing techniques advanced, image-based particle morphological analysis has enabled more rapid, objective, and repeatable means of classification [36]. High-definition cameras and scanners have been used to collect 2D image data of aggregates. Automated 3D image analysis systems including the University of Illinois Aggregate Image Analyzer (UI-AIA) and the Aggregate Imaging System (AIMS) were also developed for determining morphological parameters at multiple length scales [37–39]. The accuracy and ability of several image analysis methods have also been assessed by comparing their results to the Rittenhouse and Krumbein charts [36].

3. Materials and testing procedures

In this study, the new GAIA method was used for tests on five types of granular materials typically used for unpaved roadway surface and pavement foundation layers. To compare the results with conventional laboratory testing methods, sieve analyses and LA abrasion tests were also conducted in accordance with ASTM C136 and C131, respectively [13,40].

3.1. Materials

The five different granular material types were collected from a granular-surfaced road as well as from two quarries having different geological diagenesis. The existing surface aggregate (ESA) had the lowest gravel content (>4.75 mm), because this material had already been abraded by traffic for some time. Compared to the concrete stone (CS) material which consisted of a uniformly graded clean aggregate, the virgin surface aggregate (VSA), road rock (RR), and class A stone (CAS) were all more well graded. The sieve analysis results and Unified Soil Classification System (USCS) symbols for the five materials are summarized in Table 1.