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The effect of instrumentation on the determination of the resilient modulus of unbound granular materials using advanced repeated load triaxial testing

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ABSTRACT

Unbound Granular Materials (UGMs) are used in the base/subbase layers of flexible pavement structures for the vast majority of the main roads around the world. The resilient modulus of UGMs is a key input parameter for the design and analysis of flexible pavement structures. In the present study, four road base UGMs with a range of moisture contents are used to evaluate each material's resilient deformation behaviour using laboratory repeated load triaxial tests. The triaxial system for the tests is instrumented with four axial deformation gauges: an on-specimen axial Hall-Effect transducer, an internal Linear Variable Differential Transformer (LVDT), an external LVDT, and the actuator LVDT. The application of a Hall-Effect transducer directly mounted on the specimen and the three LVDTs permits the comparative study of alternative deformation measurements for the determination of an accurate and reliable resilient modulus value. By comparing tests results obtained with each transducer, the relative capability of each measurement is determined and a reference transducer for deformation measurement is identified. A constitutive model is then used to carry out a regression analysis and to predict the resilient modulus of the four tested materials.

Introduction

Unbound Granular Materials (UGMs) used in construction of the base/subbase layers in flexible pavements show complex elastoplastic behaviour when subjected to cyclic loading caused by moving traffic [16]. The deformation response of unbound granular layers under traffic loading is characterised by both resilient deformation and permanent deformation. The resilient deformation is associated with one of the primary damage modes, the fatigue cracking of asphalt concrete layers. The resilient response of UGMs is usually defined by the resilient modulus (M_R) and Poisson's ratio [16]. Resilient modulus, which provides a measure of stiffness, is a direct and fundamental input parameter in pavement design procedures. Comprehensive characterisation and appropriate evaluation of the resilient deformation behaviour of UGMs is essential for improving the design and functionality of flexible pavements. Over the years, numerous studies have attempted to characterise the resilient behaviour of UGMs [24,12,30,23]. It is found that the resilient properties of UGMs are affected by several factors such as: stress level, density, grading, fines content, maximum grain size, aggregate type, particle shape, and moisture content [20,26,27,14]. However, stress level has the most significant influence on resilient behaviour of granular materials [16].

Repeated Load Triaxial (RLT) test is considered as one of the most reliable laboratory experiments to evaluate the resilient deformation behaviour of pavement materials under repeated loading. Conventional triaxial testing apparatus measures the specimen deformation by a transducer positioned external to the triaxial cell. However, system compliance of the triaxial system, sample bedding effects, and specimen tilting are the main problems in acquiring precise results from triaxial tests with external transducers. Jardine et al. [13] studied the importance of measuring the soil specimen deformation locally on the specimen. He showed that the stiffness of various stiff soil specimens obtained by using the transducer external to the triaxial cell is underestimated compared to the true stiffness for local axial strains less than 10^{-4}. Clayton and Khatrush [6] developed a device that utilised a Hall-Effect semiconductor for the local measurement of strains during the triaxial test. Goto et al. [11] pointed out that it might be crucial to measure local axial strain in

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a triaxial test to perfectly exclude the bedding error in the measurements. They developed a simple device named a Local Deformation Transducer (LDT) to measure the average local strain of soil specimens (gravel, cement-treated sandy soil and soft rock) in the laboratory. They showed that the difference in the stress-strain relationship was remarkable between the internal and external measurements and concluded that use of a LDT is a useful tool to measure the stiffness of soils when subjected to both cyclic and monotonic loadings. Mohammad et al. [19] conducted resilient modulus tests on both cohesive and cohesionless soils (silty clay and sand). They instrumented the triaxial apparatus with two types of internal strain measurement systems; an LVDT located at the end of the sample, and another LVDT at the middle one-third of the specimen. They suggested a multiplier of 1.5–1.6 for M_R values determined using the end system to obtain M_R values using the middle system in an unconfined test on clays. They recommended a ratio of approximately 1.12 for sands. Maher et al. [17] employed a non-contacting proximity sensor to measure the resilient modulus of a non-cohesive and granular subbase material and compared the results with the one measured from external LVDTs. They reported that external LVDTs underestimated the resilient modulus value by about twenty percent. Boudreau and Wang [5] reported that internal measurements for load and deformation can eliminate or reduce the inherent errors associated with equipment variations to calculate the resilient modulus properties of unbound materials. Bejarano et al. [3] and PING et al. [22] also compared the results of internal and external axial LVDTs measurements for the pavement materials and granular subgrade soil, respectively. They reported a higher resilient modulus with the internal LVDT compared to the external one.

Andrei [2] conducted a study on the effect of the issues of different instrumentation setup on resilient modulus test results. He showed that when using a setup with a clamp-mounted LVDT, the results were highly variable and seemed non-repeatable even with the same test system. He argued that the membrane between the clamp and the specimen can deform in shear and the spring force in the LVDT was acting against the movement of the material preventing the clamps from getting closer to each other. As a result, the whole deformation of the specimen cannot be captured. However, attaching the LVDT to studs introduced into the specimen was found to be a successful method. A similar instrumentation setup was established by Uzan [28] and Dawson and Gillett [8]. Andrei [2] noted that the use of internal studs is promising for fine-grained materials in contrast to clamps which can easily disturb the test specimen in the area of contact with the material. However, the application of internal studs was found to be questionable for coarser materials. He reported that for coarse-grained, larger aggregate size materials the studs did not perform very well as the internal section of the stud assembly cannot find enough support and ensure the required rigidity. Finally, after several trials, he utilised the conventional setup with clamp mounted LVDT with an enlarged contact area for the base materials.

As mentioned earlier, the application of local deformation measurement transducers to minimise the errors associated with the determination of the material stiffness from triaxial test has been widely addressed in the literature. In some previous studies [17,3,22], the researchers measured the resilient modulus of UGMs by the use of different axial deformation measurement transducers. However, the sensitivity of the resilient modulus of UGMs to the measurement of the axial deformation by the Hall-Effect versus the LVDT transducers has not been investigated. To investigate such a sensitivity for different UGMs, in the presented study, a series of advanced RLT tests were carried out on four different UGMs with the use of four displacement measurement transducers which are on-specimen axial Hall-Effect transducer and three different LVDTs (internal, external, and actuator LVDTs).

By comparing and evaluating the results of each transducer, one transducer is selected as the reference one for the rest of the analysis. The errors associated with each transducer measurement are provided, and a relation between the transducers resilient modulus measurements based on the reference transducer is introduced for the tested materials. Lastly, a constitutive model is fitted to the data using a regression analysis in order to predict the resilient modulus of the materials.

RLT test method

Test materials

The laboratory tests were performed with four unbound granular base materials sourced from quarries in Victoria, Australia. The first material is crushed granite with standard plasticity (Granite Standard Plasticity, GSP), complying with the class 1 VicRoads specification for road bases [29]. The second material, identified as Granite Increased Plasticity (GIP), is crushed granite with an increased fines content passing the No. 200 (75 μm) sieve of around 10%. The GIP material also complies with the class 1 VicRoads specification despite the addition of plastic fines. The plasticity index of GSP material is 7 while the GIP material has a plasticity index of 9. The third material is crushed hornfels with standard plasticity (Hornfels Standard Plasticity, HSP), complying with the class 2 VicRoads specification for road bases [29]. The fourth material, identified as Hornfels Increased Plasticity (HIP) is crushed hornfels with increased plasticity having fines content passing the No. 200 (75 μm) sieve of around 13%. This amount of fines content exceeds the allowable fines content for class 1 and 2 road base products according to the VicRoads specification [29]. The plasticity index of HSP material is equal to 4. However, the HIP material has a plasticity index of 9 due to its higher fine fraction [4]. The particle size distribution curves of these materials are presented in Fig. 1.

Sample preparation

The granular materials were compacted using a vibratory compaction method in six layers in a steel mould at specific moisture contents and densities. The compaction force was generated by an electric vibratory hammer according to the AASHTO standard T307-99 [1] to produce cylindrical specimens of 100 mm in diameter and 200 mm in height. After compaction, specimen was extruded using a hydraulic jack from the steel mould into a plastic split mould with a rubber membrane placed inside it. A vacuum

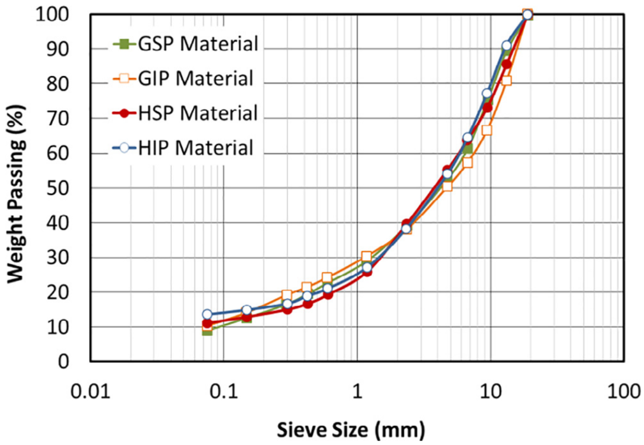

Fig. 1. Particle size distribution of the test materials [4].