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Assessment of compaction quality of multi-layer pavement structure based on intelligent compaction technology

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HIGHLIGHTS

- The intelligent compaction technology was implemented on three-layer pavement.
- The effect of moisture content on CMV was studied.
- The interactions of CMV values among multiple layers were analyzed.

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ABSTRACT

Intelligent compaction (IC) is an emerging and evolving technology for road construction. IC technology brings a lot of benefits as well as some challenges to be solved. This paper presents the framework of a field construction using IC technology and the results of the assessment of the practical use of intelligent compaction. The IC technology was implemented at the soil subgrade, the cement stabilized gravel subbase, and the cement stabilized gravel base course. The changing pattern of Compaction Meter Value (CMV) corresponding to roller passes and moisture contents of compacted materials was studied. It was found that it is more likely to achieve the desired compaction quality under the optimum moisture content situation. The relationships between CMV values and in situ measurements (compactness and deflection) for three layers were analyzed using simple linear regression analysis. The results of above linear regressions performed at three layers indicate the potential influence of underlying layers on upper layers. Then the relationships between CMVs of different layers were firstly studied using simple linear regression and multiple linear regression in which the effects of moisture content and compaction quality indicators were also considered. The study on the effect of moisture content on CMV shows that the closer the moisture content to the optimum moisture content, the more likely to get larger CMV values. The strong and consistent correlations between CMVs of different layers obtained from above regression analysis have further demonstrated the contribution of underlying layers to upper layers, and may be useful in the research of CMV decoupling in the future. Furthermore, the proposed moisture content effect study has provided a way for the above multiple factors involved CMV decoupling research in future studies.

1. Introduction

Compaction is one of the most critical steps in the process of road construction. A good compaction guarantees the service level of roads. However, the existing compaction assessment, based on manual measurements (density or moduli tests) after compaction at limited spots, has several drawbacks: (1) the testing results acquired from limited points cannot represent the compaction quality of the entire road; (2) the mentioned manual measurements could be destructive to the compacted layer; and (3) above measurements are time-consuming, making it impossible to provide real-time compaction information. The lack of real-time compaction information may lead to over or under-compaction. Meanwhile, the roller passes are usually decided by roller operators based on their experiences during conventional compactions,

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which may also cause over or under-compaction [1–3]. All the inherent shortcomings of the conventional compaction quality control (QC) method may result in a failure of long-term pavement performances and an increases of maintenance costs.

A new compaction quality management technology named Intelligent Compaction (IC) has been developed to solve the problems in conventional compaction. By consisting of an accelerometer-based vibratory roller that measures the vibration characteristics of the roller and materials under compaction, a GPS system that can precisely determine the location of roller, and a real-time feedback system reporting the compaction information on the monitor screen, IC improves the visual degree and the controllability of compaction process as an integral system [2,4]. All the compaction information including the number of roller passes, location of the roller, roller speed and vibration properties (amplitude and frequency), intelligent compaction measurement value (ICMV) reflecting the compaction quality, and even the temperatures of asphalt layers, can be displayed on an onboard computer in real time. Several ICMVs are used in practice to evaluate the compaction quality [5], such as Compaction Meter Value (CMV) [6,7], Compaction Control Value (CCV), Machine Drive Power (MDP) [8,9], vibration modulus (E_{vib}), etc [10]. For instance, CMV, which is calculated based on the mechanical interactions between vibratory drum and the layer under compaction, indicates the soil stiffness. Large CMV values indicate large stiffness, and vice versa. With the assistance of continuously updated compaction information covering nearly 100% of the area under compaction, roller operators can adjust the compaction process timely to avoid over or under-compaction, and the long-term performance of road can be guaranteed to reduce life cycle cost [11]. The applications of IC in engineering projects have shown some distinguished advantages, including the real-time feedback of compaction information, identifying the weak spots, pointedly taking remedial actions, and improving the uniformity consequently [12–15].

However, there are still problems to be addressed in popularizing IC. Firstly, by providing only an estimate value of compaction quality, IC roller is still unable to directly measure the modulus of the compacted layer or the material density which has been used as the standard compaction quality index for many years. Some methods have been developed for real-time compaction quality monitoring and control [16–20]. Imran et al. [16] evaluated the Intelligent Compaction Analyzer (ICA), which was an IC tool developed by the University of Oklahoma, in continuously measuring the dry density and modulus during subgrade compaction. The trained Artificial Neural Network (ANN) was used to determine compaction measurements and give density or modulus reading in real-time, and a well correlation ($R^2 = 0.63$) between the estimated moduli and resilient moduli was obtained. Commuri et al. [17] employed a new neural network based method to estimate the density of HMA using pattern-recognition techniques, and the results showed that the analyzer can estimate the density for quality control in real-time. However, above systems are still immature and therefore have not been widely used. Secondly, although several IC measurement values such as CMV are often employed to characterize the compaction quality, CMV might not be reliable enough to represent the compactness. The correlation between CMV and compactness (or FWD measured deflection) might be poor or instable due to multiple factors, such as soil heterogeneity and moisture content variations [21,22]. In addition, the measuring depth of CMV is about 1–1.2 m, which is much greater than the thickness of one subbase or base course layer. Therefore, the CMV measured on the upper layer is inevitably influenced by the stiffness of the underlying layers [3,15,23–25]. A method was proposed to filter the influence of the underlying layers on CMV [25]. A methodology was also developed to extract layer elastic modulus from current IC data, which included forward modeling and real-time inverse analysis using finite element analysis and boundary element analysis, making it possible to directly evaluate the elastic modulus of each single layer using IC data in the future [26].

The case study demonstrated in this paper examined the distribution patterns of CMVs corresponding to the changes of roller passes and moisture contents of compacted materials first. Then the correlations between in-situ test data (compactness and deflection) and roller measurements were investigated through statistical regressions. The compaction quality of subgrade was calculated using compactness test results and CMVs respectively. The relationships between CMVs of different layers, the effect of moisture content on CMV, and the relationships between stiffness of the underlying layer and CMVs of upper layer were further studied based on statistical analysis.

2. Background and methodologies

2.1. Construction information and in situ tests

The project studied in this paper was located in Shanxi province, China. The length of this test strip was 460 m. The IC technology was implemented at the soil subgrade, the cement stabilized gravel subbase layer with a thickness of 20 cm, and the cement stabilized gravel base course with a thickness of 20 cm as shown in Fig. 1a. The aggregate used for cement-stabilized subbase and base course was limestone, and the cement content was 5% by mass. The material information and laboratory compaction test results for all the 3 layers are summarized in Table 1.

To study how moisture contents of materials influence the intelligent compaction results, layers were segmented to sections of different moisture contents. In consideration of the non-uniformity of the soil subgrade due to its inherent heterogeneity and its natural moisture content variations, the whole soil subgrade was watered roughly using a watering sprinkler. Then before the subgrade compaction, the moisture contents of subgrade were measured on four points at each transverse section with a spacing of 10 m along the test strip with a handheld moisture detector (see Fig. 3a). The initial conditions of subbase and base course were different from that of the subgrade, and three moisture contents for different sections were set according to the laboratory compaction test results and were achieved through the mixing plant. In the subbase compaction, three test sections corresponding to three moisture contents 3.3%, 4.3% and 5.3% were prepared, whose lengths were 80 m, 150 m, and 80 m, respectively. As for the base layer compaction, three moisture contents were 3.7%, 4.7%, and 5.7%. The above arrangement is shown in Fig. 1b, in which it should be noted that two 150 m-length sections of subbase and base in the middle were arranged to study another IC indicator – Machine Drive Power (MDP), which are not discussed in this paper.

As shown in Fig. 2, intelligent compaction was performed from soil subgrade to base course in time order. It should be noted that for cement stabilized gravel layers, the curing work must be implemented. In this project, for both the subbase and the base course, curing was performed for seven days, during which the plastic film was used to cover the layer surface to guarantee the moisture content until the strength is formed.

In this test project, to assess the compaction quality, the compactness and the deflection of each compacted layer were measured respectively. After the compaction work on soil subgrade layer was completed, several test spots along the entire test strip were selected according to the different levels of CMVs to implement the compactness test using ring sampler method, see Fig. 3 (b). Compactness tests for the cement stabilized gravel subbase layer and the cement stabilized gravel base course were conducted