Automation in Construction 62 (2016) 114–123

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Real-Time Quality Monitoring and Control of Highway Compaction

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ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form 26 October 2015
Accepted 10 November 2015
Available online xxxx

Keywords:
Highway construction
Compaction quality control
Quality assessment
Real-time monitoring
Intelligent compaction

ABSTRACT

Compaction quality affects the long-term performance of highways, and thus is important in the highway construction. The current practice for compaction quality control primarily relies on the monitoring of rolling parameters such as rolling passes, speed and vibration of rollers, and lift thickness. Soil samples are randomly collected to evaluate the compactness. This practice is subject to two main limitations. First, the compaction monitoring and measurement are not always comprehensive since limited samples are manually collected. Second, compaction information cannot be disseminated to owners, supervisors, contractors, and operators in timely fashion. In this study, intelligent compaction (IC) technology is leveraged to monitor and control highway compaction quality. A new measure of compaction quality, compaction power per unit volume (E), is created and used with other IC measurement values such as compaction meter value (CMV) to achieve more reliable monitoring and assessment. Field experiments were conducted. The results demonstrated that the integration of CMV and E in the regression model leads to a higher coefficient of determination than that of using only CMV or E. A real-time monitoring system is developed, which not only evaluates the compaction quality of the entire area, but also synchronizes the compaction information among owners, supervisors, contractors, and operators in real-time. As such, this system cultivates an integrated “operator–contractor–supervisor–owner” quality control mechanism, which can improve the current highway compaction practice.

1. Introduction

Years of continual growth in the road construction have given China a vast network of highways which serve as critical links moving people and goods throughout the country. The increasing traffic demand in China requires the acceleration of highway construction. The highway mileage in China increased from 104,000 km in 2013 to 111,450 km in 2014. It is projected that 4700 billion RMB will be invested to further increase the highway mileage to 400,000 km through 2030. However, under such extensive expansion, many highway projects have experienced a litany of undesired quality issues. For example, pavement distresses such as cracking and rutting occur in a short period. A number of highways even structurally failed in half a year. One of the leading cause of these flaws and failures is the poor quality control practice in highway compaction. The inadequate quality control practice often results in a number of quality flaws. For example, pavement thickness is not compliant with the standard, and pavement is not uniformly compacted to the described density. Because the failure and accelerated deterioration of highways cause enormous economic loss, it is imperative to improve the monitoring and control of highway compaction quality.

Compaction quality monitoring and control is critically important in the highway construction, because compaction quality affects the durability and long-term performance of pavement. Ensuring subgrade to be compacted as specified is an essential task in compaction quality control. The current practice in China primarily relies on the monitoring and control of rolling parameters such as rolling passes, speed and vibration of rollers, and lift-thickness. Samples are randomly collected to evaluate the compaction quality [1]. However, this practice is subject to a number of limitations. For instance, the reliability of compaction quality of the entire subgrade is suspicious because only limited samples are collected for testing. The manual sample collection interrupts subsequent activities and can be destructive to the compacted subgrade. The laboratory testing is time-consuming, which cannot provide real-time information of compaction quality. The lack of real-time compaction information can result in insufficient and/or excessive compaction.

Intelligent compaction (IC) technologies have emerged to improve current compaction practice. Specifications pertaining to IC technology applications in the highway construction have also been developed [2]. Despite these advancements, two main challenges still remain to be addressed. First, many IC measurement values such as compaction meter value (CMV) have been adopted to indicate the compactness. However, CMV might not always be adequately reliable in reflecting the compactness. For instance, the relationship between CMV and

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http://dx.doi.org/10.1016/j.autcon.2015.11.007
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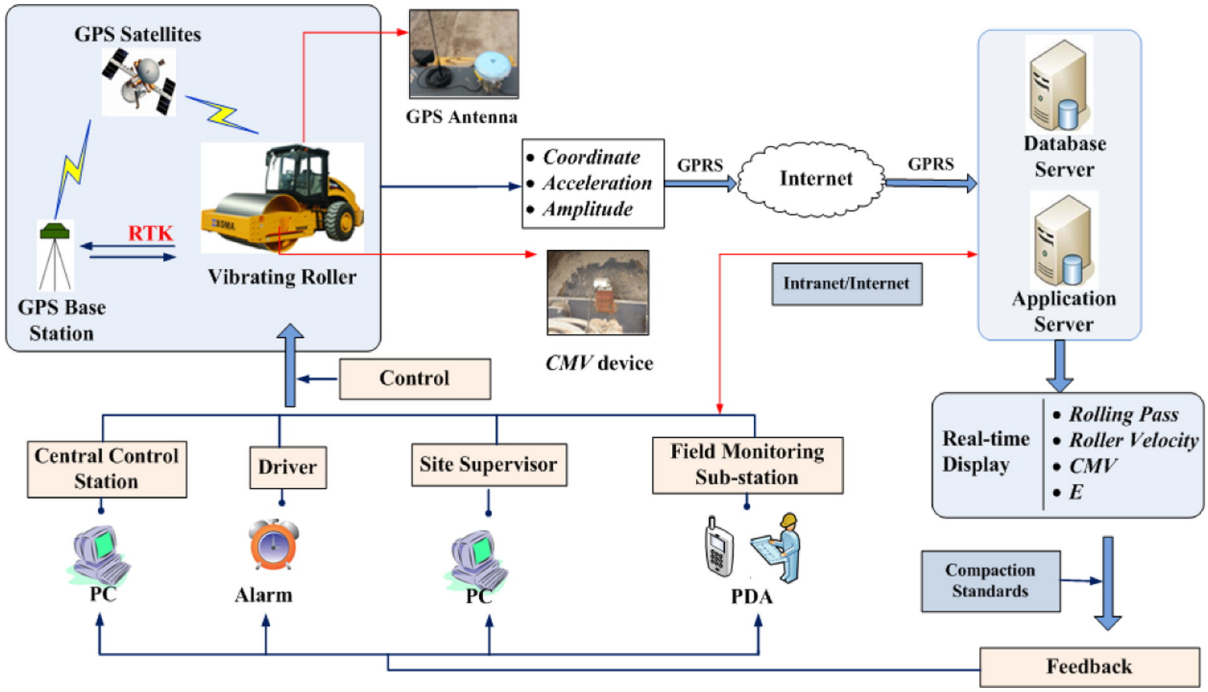

Fig. 1. Real time monitoring for highway compaction quality.

compactness might be adversely affected by the underlying layers [3]. Hence, there is a need to improve the reliability of IC measurement value in estimating compactness. Second, most IC technologies only provide real-time compaction information to machine operators. However, machine operators are often not incentivized to ensure compaction quality. This is particularly true in China, since contractors are often awarded with very low price contract. Compaction quality concerns owners and supervisors, but they usually lack real-time compaction information for continuous and responsive quality control. Thus, there is a need to disseminate the compaction information to operators, contractors, supervisors, and owners in a timely fashion.

To address the first challenge, compaction power per unit volume (E) is created in this study as a new IC measurement value, which can be used with other IC measurement values such as CMV to achieve

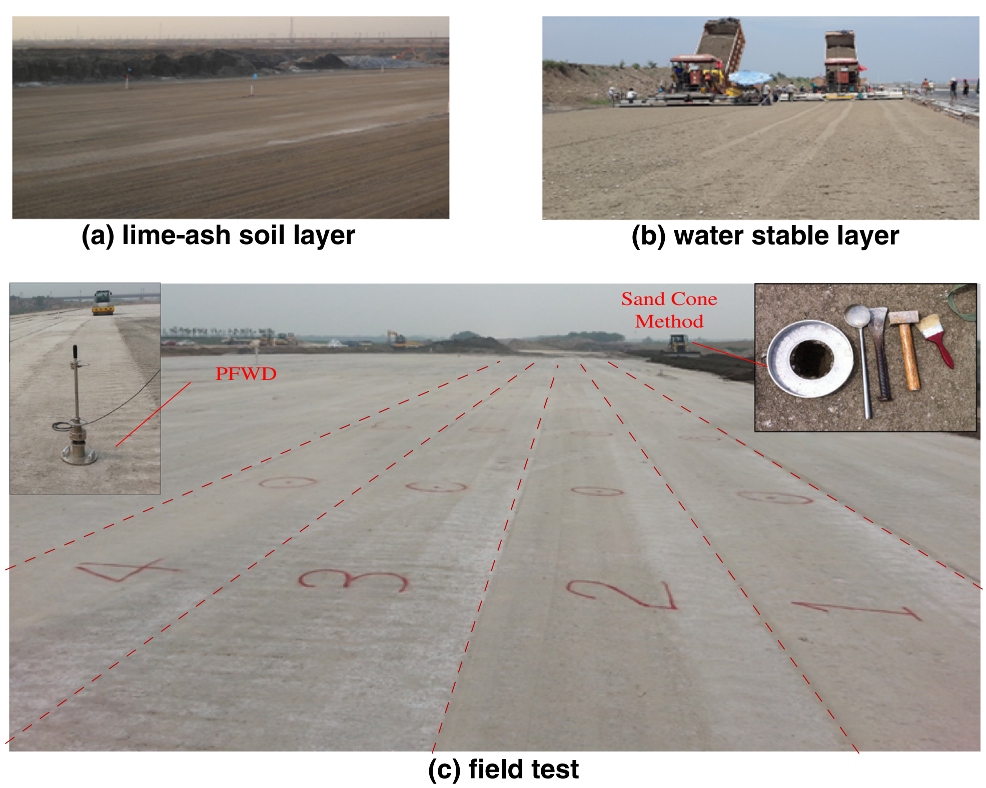

Fig. 2. Filed experiments settings.

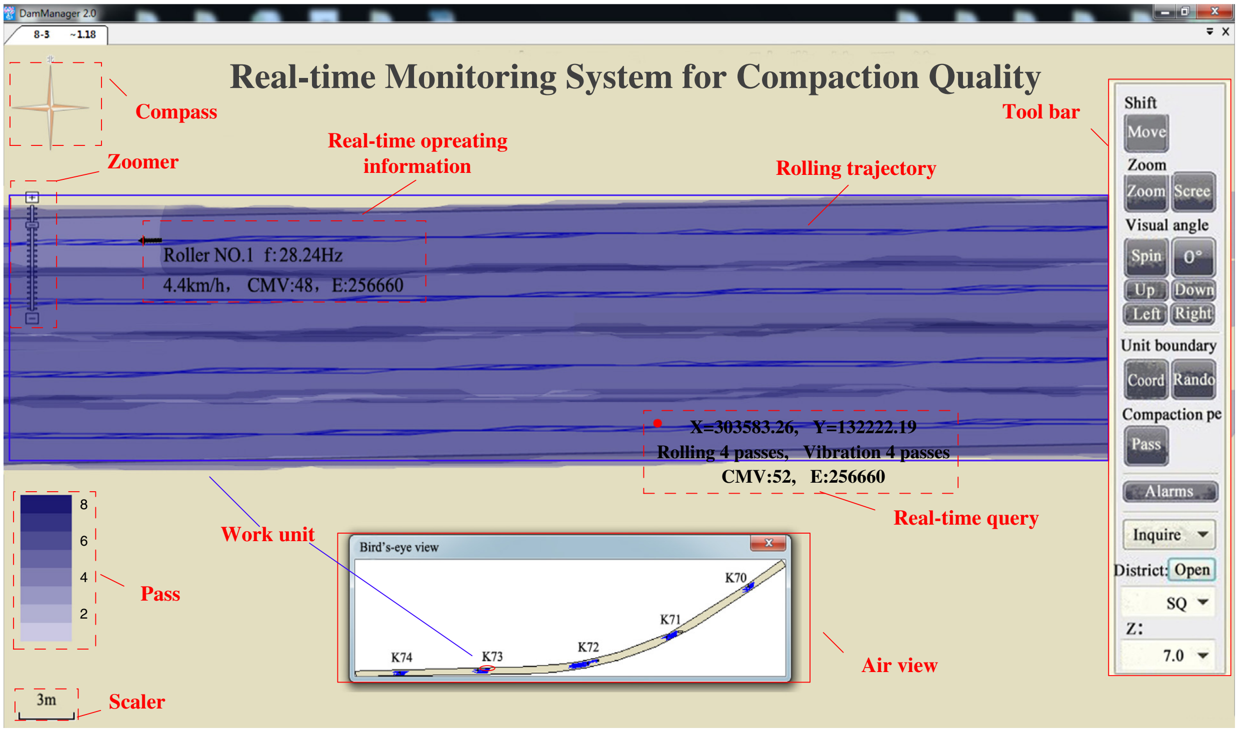

Fig. 3. User interface of real-time system for monitoring compaction quality.

more reliable compactness assessment. To address the second challenge, a real-time system is developed to monitor compaction and synchronize the information among operators, contractors, supervisors, and owners to realize an integrated quality control mechanism. The remainder of this paper is structured as follows. Next, the studies related to intelligent compaction is reviewed. Then, the research objectives are presented, and the value of this research is underscored. Thereafter, the derivation of compaction power per unit is illustrated, and the development of the real-time monitoring system is described. Field experiments were conducted to validate the newly created IC measurement value and system. Finally, the research findings and implications, limitations and future research directions are discussed to close the paper.

2. Literature review

Intelligent compaction systems have been used in the highway construction for continuous evaluation of mechanistic soil properties through roller vibration monitoring [3]. Studies related to intelligent compaction measurement values, data analyses, and monitoring systems are reviewed in this section.

2.1. Intelligent compaction measurement values

There are a number of intelligent compaction measurement values used in practice [4–5]. Compaction meter value (CMV), developed by Geodynamik in 1978 [6], is used by Dynapac, Caterpillar, and Volvo to reflect the compactness of soils [7]. CMV can indicate the presence of buried objects such as rocks and clay balls that may affect the quality of the base. In addition, CMV can indicate soil stiffness. Large CMV values indicate stiff soil while small CMV values indicate soft soil. Although CMV has been widely adopted [8–9], it is not always reliable in reflecting the compactness. In addition, the empirical relationships between CMV and soil density, stiffness, and modulus are affected by a number of factors. For instance, CMV typically measures 1 to 1.2 m deep, which is greater than a 15–30 cm thick layer or lift of subgrade, subbase, or base material. Hence, CMV values are easily affected by the underlying layers and sometimes might not be informative [10]. In 2004, Sakai introduced the compaction control value (CCV) [11]. CCV is a derivative of CMV, which uses harmonic content from the measured drum vibration to estimate the compactness. In the late 1990s, Bomag introduced a vibration modulus E_{vib} that serves as a measure of dynamic soil stiffness [12]. In 1999, Ammann developed soil stiffness parameter k_s or k_B [13]. The introduction of E_{vib} and k_B showed a trend

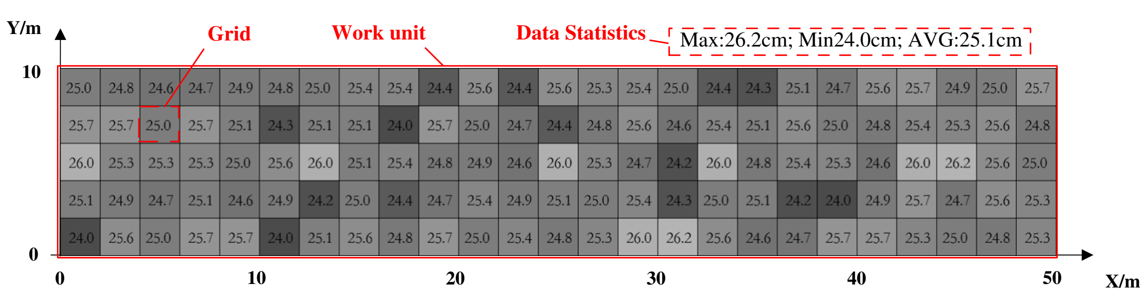

Fig. 4. Graphical report of compacted thickness for lime–ash soil layer.

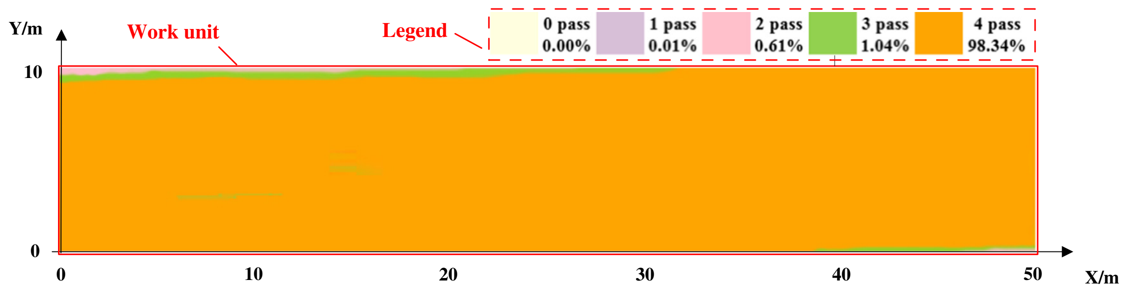

Fig. 5. Graphical report of rolling passes for lime–ash soil layer.

toward the measurement of mechanistic, performance-related soil properties [3]. In addition to CMV, Caterpillar also uses machine drive power (MDP) as a measure of soil compaction. MDP measures the stresses on the drum and the energy necessary to overcome the resistance to motion. High MDP values indicate soft or weak material, while low MDP values indicate compact or stiff material [14–15].

2.2. Data analyses for compaction monitoring

The relationships between measurement values and compactness have been investigated in many studies. Mooney et al. [16–17] investigated the correlations between CMV, CCV and spot-test measurements (i.e., dry density and dynamic cone penetrometer (DCP) index) for sand soil in subgrade and crushed rock material in base. Their studies found that the correlations improve significantly if the underlying materials are stiff. White and Thompson [8] conducted a field study to correlate CMV to spot test measurements (i.e., dry unit weight, DCP index, Clegg impact value (CIV) and light weight deflectometer (LWD) modulus) for granular soils through linear regression. In their study, high correlations were observed ($R^2 > 0.9$). White et al. [8] performed field investigations to examine the correlations between CMV and spot test measurements. Correlations were found between CMV and DCP index and between CMV and dry unit weight. Thompson and White [18] employed multiple linear regression analyses to explore the relationships between CMV, MDP, moisture content, and spot test measurements (density, DCP, CIV). R^2 was between 0.85 and 0.95 for correlations between measurement values (CMV and MDP) and spot test measurements (DCP and CIV). With respect to density, R^2 was 0.68 for CMV, and 0.92 for MDP. Thompson and White [19] evaluated MDP technology for measuring the compaction parameters of cohesive soils. The influences of soil type, moisture content, and lift thickness on machine power response were considered in their study. High correlations between compaction measurements and MDP were found when the moisture content and MDP-moisture interaction terms were included in their regression models. Moreover, Kröber et al. [12] explored the relationship between E_{vib} and plate load test (PLT) moduli through field tests. Their results exhibited a linear correlation between E_{vib} and PLT moduli with $R^2 > 0.9$. However, Petersen [20] found poor correlations between E_{vib} and spot-test. In addition, Vennapusa et al. [21] proposed an approach to characterize and quantify non-uniformity of compacted earth materials using spatially referenced roller-integrated compaction measurements and semivariogram based geo-statistical analysis. Xu et al. [22] proposed a systematic method that uses both the univariate and geo-statistical modeling techniques for IC data analysis and management.

2.3. Compaction monitoring systems

Mooney et al. [3] reviewed a number of compaction monitoring systems that are used by various IC manufacturers. Anderegg and Kaufmann [23] described the ACE Plus system that calculates soil stiffness during compaction. Ammann employs the ACE Plus system to map a number of roller parameters in a graphical view. Minchin Jr. et al. [24] introduced a patented system which can render the material density in real time. Bomag uses the Variocontrol system that calculates the vibration modulus E_{vib} based on lumped parameter vibration theory and cylinder on elastic half-space theory [3]. The Dynapac Compaction Meter uses the Dynapac Compaction Analyzer (DCA) and Dynapac Compaction Optimizer (DCO). DCO performs feedback control of the eccentric excitation force. Roller data including CMV, rolling passes, amplitude, frequency, GPS coordinates are collected by DCA and field computers. The data are communicated in graphical format to the operator. Caterpillar's Compaction Viewer is placed within the operator's field of view, which displays real-time position and compaction values.

Zhong et al. [25–26] and Liu et al. [27] developed a real-time system for monitoring compaction quality in the earth-core rock-fill dam construction. Their system can achieve a comprehensive monitoring of compaction parameters (i.e., rolling passes, speed, vibration states, and compacted thickness). Oloufa et al. [28] developed a real-time compaction monitoring system using GPS, sensing techniques, and wireless communication technologies. The system monitors can effectively control the rolling passes and ensure the compaction uniformity. Bharath et al. [29] developed AutoPave system that can automatically calculate the optimal rolling passes, and monitor the rolling passes and trajectories during construction.

3. Research objectives and significance

The research objective is twofold. First, we aim to create a new measure for compactness, i.e., compaction power per unit volume (E). The

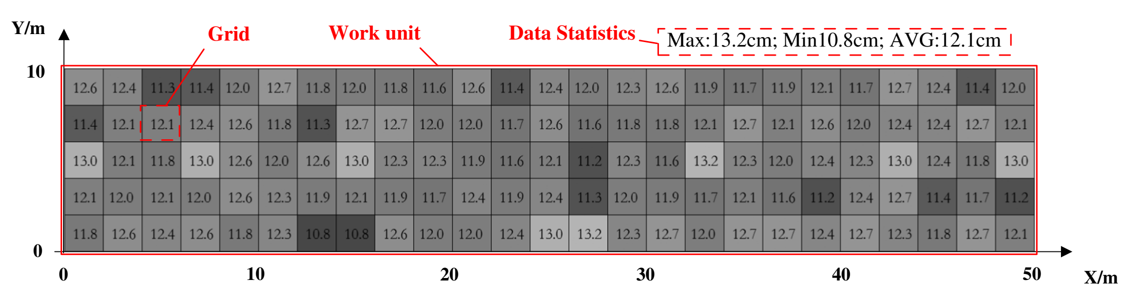

Fig. 6. Graphical report of compacted thickness for water stable layer.

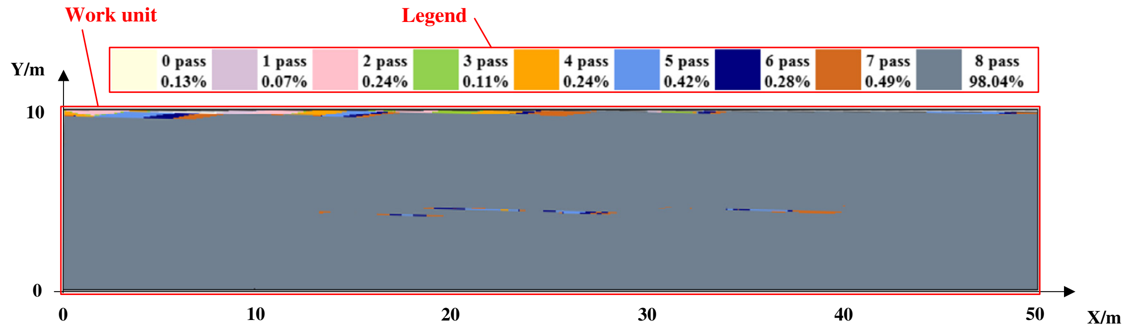

Fig. 7. Graphical report of rolling passes for water stable layer.

compaction power exerted by the roller on the materials can reflect the compactness of the materials. Two hypotheses are verified through filed experiments in this study to confirm the value of the newly created measure. The first working hypothesis is that there is a correlation between the compaction power E and the compactness. The second working hypothesis is that this new measure E can be used with other intelligent compaction measurement values such as CMV to achieve a more reliable measurement of compactness than relying on only CMV or E. Second, we aim to develop a real-time monitoring system to synchronize compaction information among operators, contractors, supervisors, and owners to cultivate an integrated quality control mechanism.

This research is significant. First, only relying on CMV might wrongly indicate the material stiffness. The integration of CMV and E has potential to overcome this limitation, thus increasing the practical value of IC technologies. Second, the system can comprehensively evaluate the compaction quality and disseminate compaction information to operator, contractor, supervisor, and owner. This integrated quality control mechanism is expected to greatly improve the quality control and assurance practice in the highway construction.

4. Methodology

This section elaborates the building blocks of our systems, which include the creation of compaction power per unit volume, the adoption of compaction meter value, and the development of real-time monitoring and control system.

4.1. Compaction power per unit volume

According to vibration theory [7], the force exerted by the roller can be calculated as Eq. (1).

$$P = W + F \sin \omega t. \tag{1}$$

W is the radial load of the roller, F is the exciting force, ω is the angular frequency of the roller vibration, and t is the time.

Due to damping effects, the movement of roller lags behind the eccentric mass. There exists a phase-difference of ϕ. The compaction power exerted on the materials in a vibration cycle is captured in Eq. (2).

$$E_s = WA(1 + \sin \phi) + \frac{1}{2} FA\left[\cos \phi + \left(\phi + \frac{\pi}{2}\right) \sin \phi\right]. \tag{2}$$

E_s is the compaction power in a vibration cycle, and A is the amplitude of the roller vibration.

φ approximates to $\frac{\pi}{2}$ as the frequency of the roller vibration approximates to 30 Hz. Typically, the rated vibration frequency of the roller used in the highway construction is about 30 Hz. Approximately, in this research, φ is considered to be $\frac{\pi}{2}$. The total compaction power per unit volume of materials after n passes can be calculated using Eq. (3).

$$\mathrm{E} = 2A\left(W + \frac{\pi F}{4}\right) \frac{fN}{Bhv}. \tag{3}$$

E is the total compaction power per unit volume, f is the vibration frequency of the roller, and B is the width of the roller, h is the thickness of compacted pavement layer, v is the speed of the roller, and N is the rolling passes.

The exciting force can be obtained in real-time through Eq. (4).

$$F = Me\omega^2 = Me4\pi^2 f^2. \tag{4}$$

M is the mass of the eccentric block, e is the eccentricity, and f is the frequency. If M and e cannot be obtained directly, an alternative calculation method for exciting force is shown in Eq. (5).

$$F = \frac{Me4\pi^2 f^2}{Me4\pi^2 f_R^2} \cdot F_R = \frac{f^2}{f_R^2} \cdot F_R \tag{5}$$

f_R and F_R are the rated frequency and excitation.

4.2. Compaction meter value

Compaction meter value (CMV) is a dimensionless compaction measure developed by Geodynamik. CMV depends on drum diameter and weight, and roller operating parameters such as frequency and amplitude of drum vibration, and speed of roller. CMV can be determined based on the dynamic roller response [15], and is calculated using Eq. (6)

$$\mathrm{CMV} = C \cdot \frac{A_{2\Omega}}{A_\Omega}. \tag{6}$$

C is a constant, the value of which is usually 300. $A_{2\Omega}$ is the amplitude of the first harmonic component of the vibration acceleration, and A_Ω is the amplitude of the fundamental component of the vibration acceleration [30].

Table 1
Compacted thickness of lime–ash soil layer and water-stable layer.

Layers	Designed thickness (cm)	Maximum thickness (cm)	Minimum thickness (cm)	Average thickness (cm)	Varying range (cm)
Lime–ash soil layer	25.0	26.2	24.0	25.1	2.2
Water stable layer	12.0	13.2	10.8	12.1	1.4

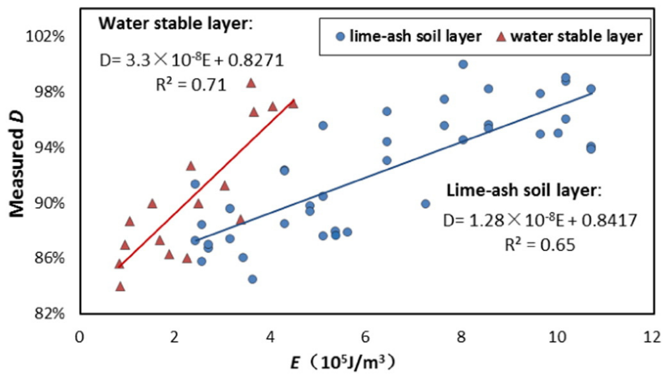

Fig. 8. Linear regression between compaction power E and measured density D.

4.3. Real-time monitoring system for compaction quality control

Fig. 1 illustrates the configuration of the real-time system for compaction quality monitoring and control. The system consists of global positioning system (GPS) locating module, IC measurement module, database and application server, control center, control substations in the field, monitoring client, monitoring terminal on roller, and Personal Digital Assistant (PDA). The monitoring process is detailed as follows.

(1). The position of the rollers can be obtained through GPS in real-time. RTK techniques are employed to ensure that the positioning accuracy achieves 1–3 cm in horizontal, 2–5 cm in vertical. The collected location data are then communicated to the database and application server through general packet radio service (GPRS) network.

(2). The layer to be compacted is divided into grids. Each grid is numbered. The calculation of roller speed v_t at time t, rolling passes $n_{k,t}$ in grid k at time t, and compacted thickness H_k in grid k are shown through Eq. (7) to Eq. (10).

$$v_t = f_v(P_t) = \frac{|P_t - P_{t-1}|}{T_t - T_{t-1}} = \frac{|P_t - P_{t-1}|}{\Delta t}. \tag{7}$$

Δt is the time interval between samplings, and $|P_t - P_{t-1}|$ is the Euclidean distance between two successive points P_t and P_{t-1}.

$$n_{k,t} = f_n(P_t) = \begin{cases} n_{k,n-1} + 1, & (x_t, y_t) \in \Omega_k, \\ n_{k,t-1}, & (x_t, y_t) \notin \Omega_k, \end{cases} n_{k,0} = 0, \tag{8}$$

$(x_t, y_t) \in \Omega_k$ means that in the tth time interval, the trajectory point (x_t, y_t) is in the kth grid Ω_k.

The compacted thickness $h_{k,t}$ in grid k at time t is computed using Eq. (9).

$$h_{k,t} = f_h(P_t) = z_t - Z_{k,0}. \tag{9}$$

Hence, the compacted thickness in the kth grid can be calculated using Eq. (10).

$$H_k = \max_t\{h_{k,t}\} = Z_{k,1} - Z_{k,0}. \tag{10}$$

z_t is the elevation at time t. $Z_{k,0}$ is the initial elevation of grid k. $Z_{k,0}$ is in accordance with the pavement design. It should be noted that $Z_{k,0}$ is not constant, since different section may have different initial elevation. The elevation of the grid k after compaction is captured in Eq. (11).

$$Z_{k,1} = \max_t\{z_t | (x_t, y_t) \in \Omega_k\} \tag{11}$$

(3). An accelerometer is installed in the drum of the roller to record the vertical acceleration of drum. Fast fourier transform (FFT) is used to transform the signals from time domain to frequency domain. The fundamental frequency is the exciting frequency of the roller. Eq. (6) is then used to calculate the CMV values in the database and application server.

(4). Eq. (5) is used to compute the output of the exciting force of roller. Following step (2), the speed v_t, rolling passes$n_{k,t}$, and compacted thickness H_k can be calculated. Consequently, Eq. (3) can be used to calculate the compaction power per unit volume. Thereafter, the data collected are aligned based on the sampling time. As such, the trajectory of roller can be generated, and the compaction information including roller speed, rolling passes, CMV and E can be monitored.

(5). The monitoring terminals in control center and substation can evaluate the compaction parameters (i.e., roller trajectory, rolling passes, compacted elevation and compacted thickness) in real-time. If there are deviations from the specified standards, warning messages will be issued to provide guidance to the relevant personnel.

(6). The roller trajectory, speed, rolling passes, compacted elevation and thickness are stored in the database, which could assist in the assessment of overall compaction quality.

4.4. Compaction quality assessment based on CMV and E

Based on the compaction power per unit volume E and CMV collected in real time and the compactness measured at test spots, regression

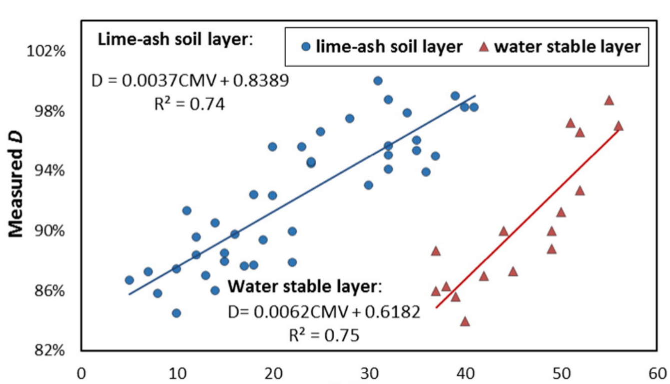

Fig. 9. Linear regression between CMV and measured density D.

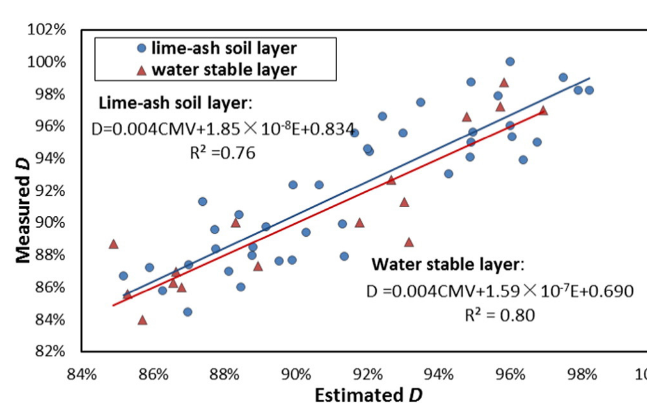

Fig. 10. Linear regression between estimated density and measured density.

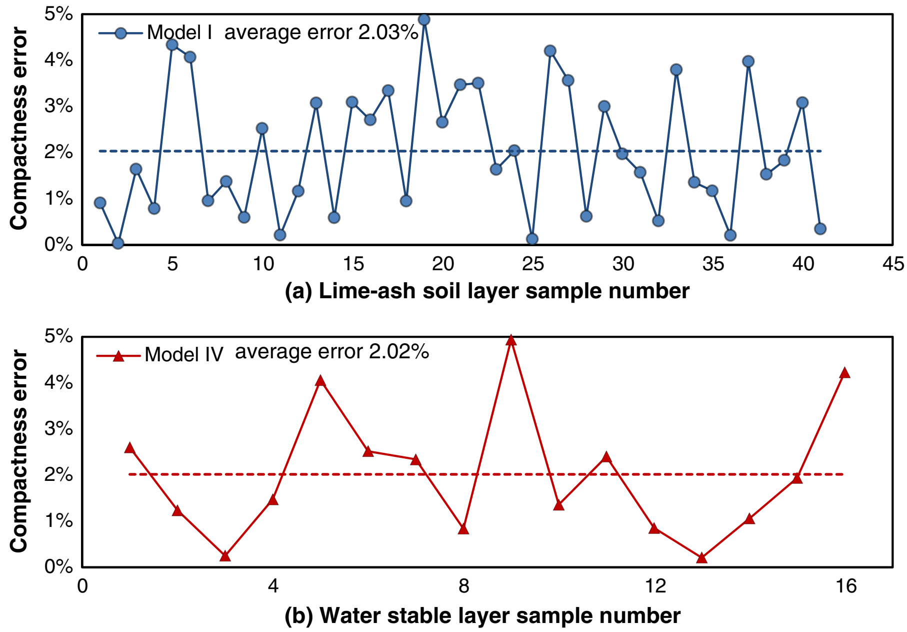

Fig. 11. Compactness error when only E is considered.

models can be built to relate E and CMV to the compactness of the subgrade (i.e., lime–ash soil layer and water stable layer). The regression models also incorporate the soil moisture, since soil moisture may affect the compactness. The steps of compaction quality assessment are elaborated as follows.

(1). *Sample collection through field experiments*
A number of field experiments need to be arranged to collect adequate sample data. First, test strips and test spots need to be marked and recorded. The compactness D, soil moisture ω, and CMV and E values at these test points need to be measured.

(2). *Correlation analysis*
The correlations between D and E, CMV and ω need to be examined for lime–ash soil layer and water-stable layer, respectively. If the correlation between one variable and compactness is insignificant, that variable should be eliminated from the regression model.

(3). *Regression model building*
Based on the sample data and correlation analysis, regression models can be built.

(4). *Compactness measurement*
E and CMV can be measured in real-time during the compaction process using the developed system. Employing the regression models in step (3), the measured E and CMV can be used to estimate the compactness D in real-time.

(5). *Spatial interpolation of compactness*
There are time intervals between the sampling of E and CMV. Consequently, the sampling points are discrete. Kriging

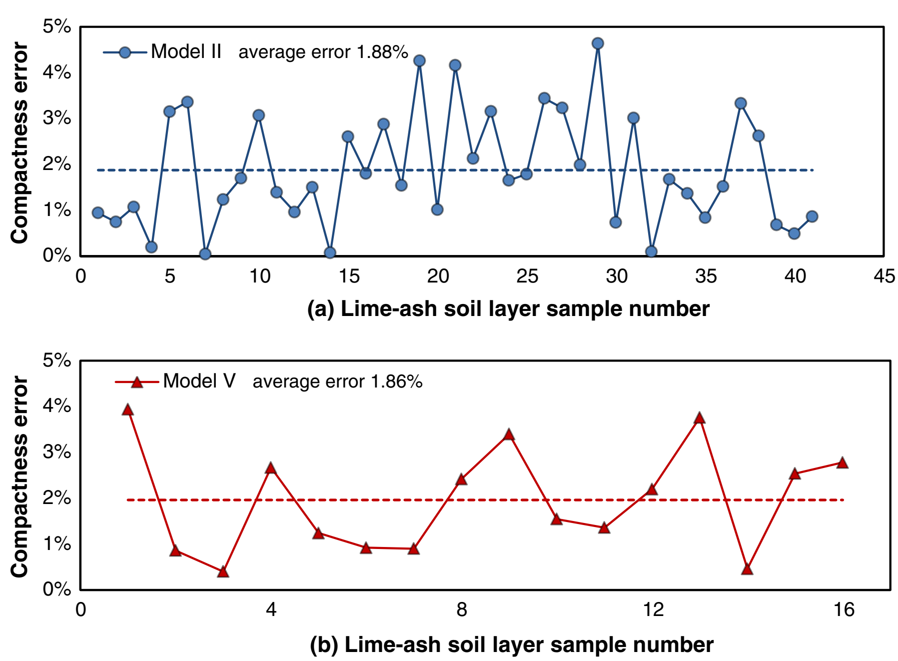

Fig. 12. Compactness error when only CMV is considered.

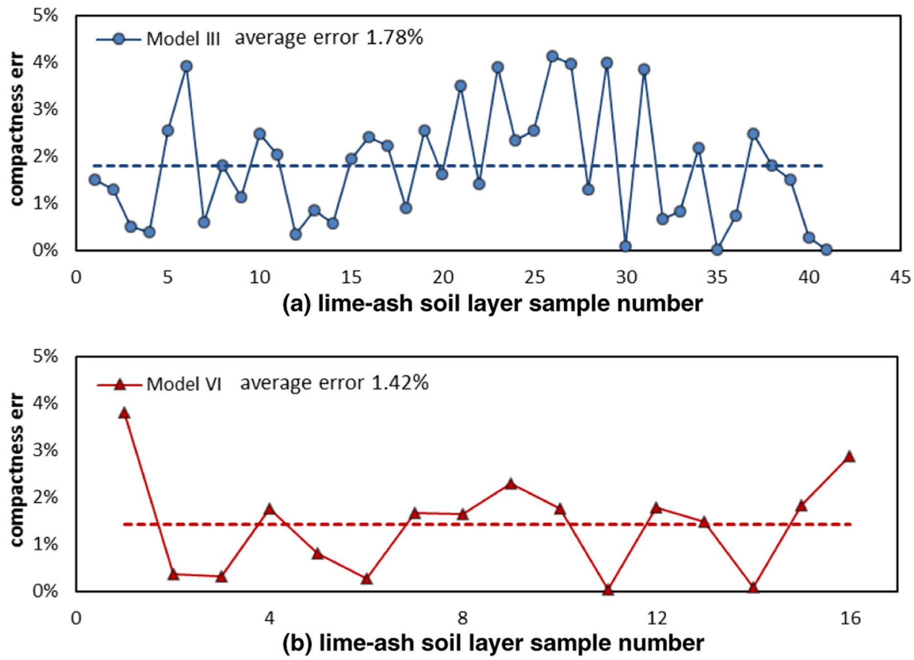

Fig. 13. Compactness error when both E and CMV is considered.

interpolation method is used to obtain the compactness at any points on the layer.

(6). *Uniformity analysis of the compactness*
Coefficient of variance (COV) can be used to measure the uniformity of compactness. COV is ration of standard deviation to the mean value of compactness. Dividing the entire layer into small grids (e.g., 0.5 m × 0.5 m in this study), the compactness of each grid can be obtained. Therefore, the standard deviation and mean value of compactness can be obtained. Typically, the smaller the coefficient of variation is, the better compactness uniformity will be [31].

(7). *Compaction quality evaluation of the whole working surface*
The compactness at any points of the working surface can be checked against the pre-defined compactness control standards to ensure the compaction quality. Different colors are used to distinguish the qualified and unqualified areas. This visualized information can guide the subsequent compaction and rework on the unqualified areas. The overall assessment of compaction quality can be estimated using Eq. (12).

$$\mu = \frac{S_D}{S_A} \times 100\% \tag{12}$$

where μ is the qualification rate, and S_D is the area where IC measurement value is greater than the pre-determined value. S_A is the total area of the surface. Larger μ indicates better compaction quality.

5. Field experiments

Field experiments were conducted to test the hypotheses and demonstrate the efficacy of the real-time system for compaction quality monitoring and control. The filed experiments were carried out in the construction site of the west outer ring highway project in Binhai district, Tianjin. The subgrade is lime–ash soil layer and the base is water-stable layer. According to the construction requirement, lime–ash soil layer needs four rolling passes, and water-stable layer needs eight rolling passes.

5.1. Field test arrangement

Four test strips were marked on a 10 m × 50 m test area, as shown in Fig. 2. Within each test strip, a number of test spots were designated for both the lime–ash soil layer and the water-stable layer. GPS was used to accurately obtain the 3D coordinates of these test points. The time when the roller passed a test spot was also recorded.

Liu et al. [32] described the relation between the compactness D of lime–ash soil and the elastic modules E_v that are measured using Portable Falling Weight Deflectometer (PFWD). The elastic module E_v is used to calculate the compactness of the lime–ash soil layer. Three points were marked in each strip. After each rolling pass, PFWD was used to measure the elastic module. Sample soils were collected to measure the moisture. CMV and compaction power E were also calculated. A total of 41 sample datasets of E_v, E, CMV, and ω were obtained after eliminating the outliers.

For water-stable layer, 4 test points were designated for each test strip. Only one data set was obtained at each test point, since the test holes are destructive to the pavement structure. The tests were conducted to obtain the compactness D and moisture ω when the number of rolling passes is even. A total of 16 datasets of D, E, CMV, and ω were obtained.

5.2. Real monitoring and evaluation

During compaction, the server receives monitoring information sent by the monitoring terminal, and the client retrieves the processed information from the database. The trajectory of the roller, vibration frequency, CMV and E values can be visualized in real-time. When the states of the roller vibration are not compliant with compaction requirement, the application server will send warning message to monitoring client (PC) and PDA in the field. Hence, operators can be guided to adjust the roller and conduct subsequent compaction. The compaction information can be inquired at any point on the surface. Fig. 3 shows the interface of the monitoring system.

Figs. 4 and 5 present the compacted thickness and number of rolling passes for lime–ash soil layer. Figs. 6 and 7 show the compacted thickness and number of rolling passes for water-stable layer. In Figs. 4 and 6, the numbers in 2 m by 2 m grids indicate the compacted

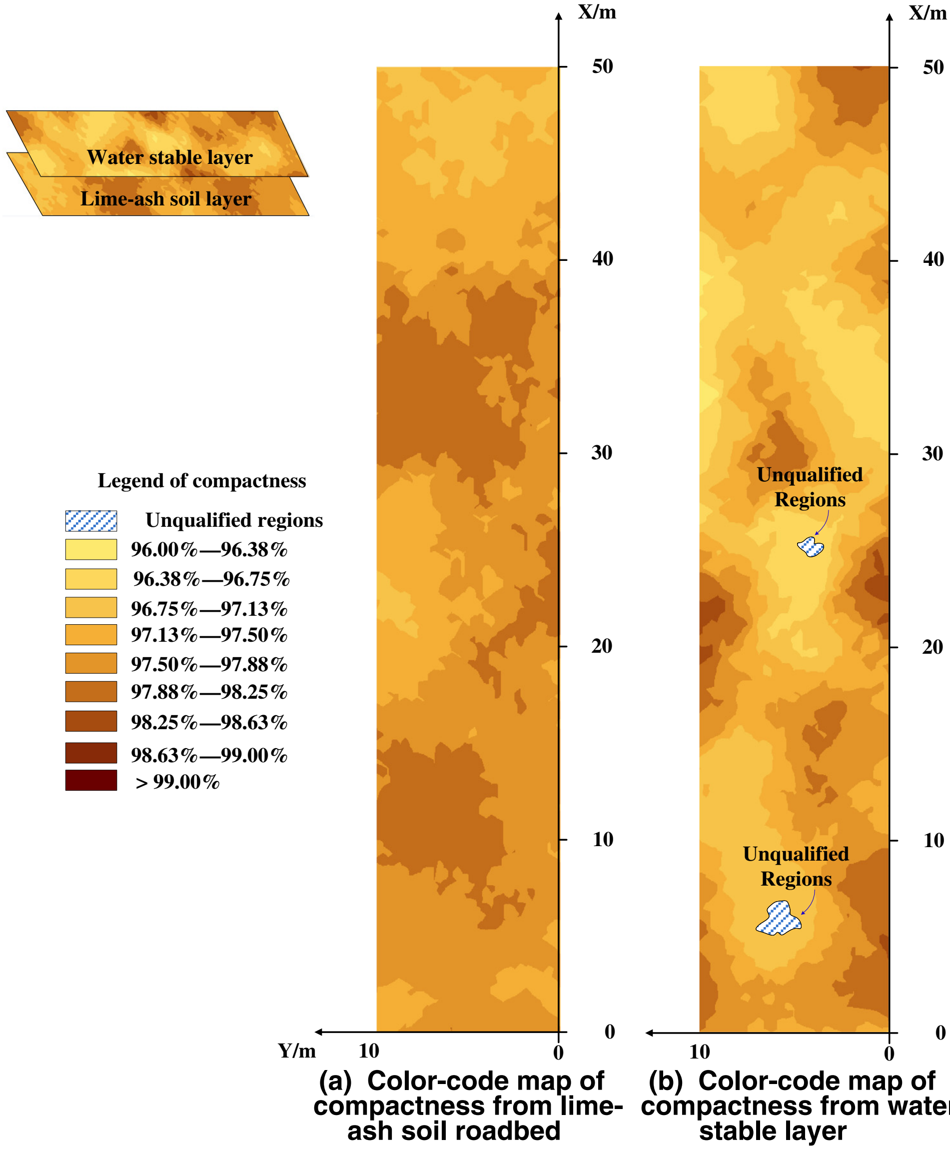

Fig. 14. Color-coded map of compactness for two layers.

thickness. In Figs. 5 and 7, the number of rolling passes are indicated by different colors. The percentage of rolling passes are also given in Figs. 5 and 7. The required compacted thickness, maximum compacted thickness, minimum compacted thickness and average compacted thickness for lime–ash soil layer and water-stable layer are presented in Table 1.

5.3. Compactness regression model building

The moisture of lime–ash soil layer is about 6.5%, and the moisture of water-stable layer is around 4.4%. Given that the material was obtained from the same source and due to the strict control in this project, the variation of moisture is small. In addition, the correlation between the moisture and the compactness is not significant in this case. Therefore, the moisture is eliminated from the regression models.

Regression models between IC measurement values and compactness are built for the two layers. It can be seen from Figs. 8 and 9, R^2 is 0.65 for lime–ash soil layer and 0.71 for water stable layer when only E is considered in the regression model. R^2 is 0.74 for lime–ash soil layer and 0.75 for water stable layer when only CMV is considered in the regression model. In Fig. 10, when both E and CMV are used to reflect the compactness, R^2 improves to 0.76 for lime–ash soil layer and 0.80 for water-stable layer. This implies that the integration of CMV and E is superior to using only CMV or E to measure the compactness in the two layers.

Figs. 11, 12 and 13 present the errors of using E, CMV and combination of CMV and E to reflect the compactness in lime–ash soil layer and water-stable layer. It can be observed that when both E and CMV are considered in the regression model, the average errors are reduced

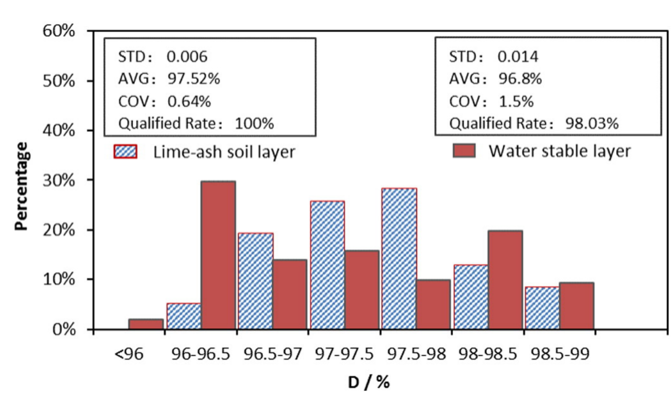

Fig. 15. Statistics of uniformity of compactness.

compared to those of using only CMV or E in the regression models. This indicates that the compaction power per unit volume and CMV complement each other, which improves reliability and accuracy of the measurement.

It should also be noted that if the designed mixture ratio changes and/or the changes of moisture is significant, the regression models need to be rebuild to consider the changes.

In this project, the compactness control standard is that D ≥ 96%. Using Kriging interpolation method, the graph of the compaction quality on the whole surface can be generated, as shown in Fig. 14. The non-compliant areas can be identified, which is the shaded part in Fig. 14. According to Eq. (12), the compaction qualification ratio for lime–ash soil layer and water-stable layer is 100% and 98.03%, respectively. The coefficient of variance for lime–ash soil layer and water-stable layer is 0.64% and 1.5%, respectively, as shown in Fig. 15. This indicates that the compaction uniformity of lime–ash layer is better than that of water-stable layer. Hence, water-stable layer needs additional compaction to ensure the compaction quality.

6. Conclusions

This study created the compaction power per unit volume (E) as a novel compactness measure. Field experiments were conducted to verify two hypotheses. Acceptable correlation between E and compactness was observed in lime–ash soil layer and water-stable layer. The coefficient of determination R^2 is 0.65 for lime–ash soil layer and 0.71 for water-stable layer. This verified the first hypothesis that E can be used to indicate soil compactness. In addition, comparisons of regression models revealed that incorporating both CMV and E into the regression model achieves a higher coefficient of determination. This verified the second hypothesis that E and CMV complement each other, and the integration can realize more reliable measurement of compactness. Improving coefficient of determination is not trivial. Specifications pertaining to the use of roller-integrated measurement values have been implemented in Austria, Germany, Sweden, and United States. Almost all of the specifications require the regression coefficient higher than a threshold to accept the use of IC technologies. Hence, the improvement of regression coefficient described in this study should be considered in the practice. To improve the quality control practice, this study developed a real-time system that combines roller-based measurement values (CMV and E) with GPS-measured positions to provide continuous assessment of compactness with a 100% coverage of the compacting area. This constitutes a significant improvement over the limited coverage provided by spot test methods. Moreover, this system synchronizes the compaction informatics among the operator, contractor, supervisor, and owner. This "operator–contractor–supervisor–owner" integrated quality control mechanism is conducive to improve the compaction quality in the highway construction.

Future research will be conducted in three aspects. First, extensive field experiments need to be conducted to collect adequate data for evaluating the performance of the system in different context (e.g., different soil conditions). Second, the moisture and the interaction between the compaction power and moisture need further investigation. Third, the spatial errors of the IC measurements and GPS positioning should be further examined to sharpen the understanding of the uncertainties in estimating compactness.

Acknowledgment

This research was funded by the State Programs of Science and Technology Development of China (No. 2013CB035902), the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (No. 51021004), the National Natural Science Foundation of China (No. 51479132), and the Tianjin Municipal Science and Technology Pillar Plan Program (No. 13CZDSF01800).

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