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Research Article

A Study on the Analysis of the Ground Compaction Effect According to the Roller Operation Method through CMV Analysis Using IC Rollers

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In road construction, the compaction process using vibratory rollers is essential to increase the ground stiffness in earthworks. There need to be clear standards regarding the operation of compaction rollers during compaction work. Various simple quality inspection techniques have been developed to check the stiffness of the ground, but plate load test and field density test are the most commonly used test methods to evaluate the degree of compaction during road construction. However, both inspection methods could be more efficient, as they cannot be performed in all sections due to time and cost. Additionally, in compaction work today, the worker will individually judge the number of compactions, thickness, speed, vibration etc. based on his or her own experience. This means that the quality of compaction varies depending on the worker. In this study, quality inspection results for all sections were obtained using an intelligent quality control system that employs an IC roller, a technology that is now commercially available. The effect of the operating conditions of the vibrating roller (roller compaction direction, compaction roller speed, and compaction roller vibration method) on the compaction quality was analyzed using the intelligent quality control value. Through our highway construction site tests, it was found that the speed of the compaction roller and the vibration method of the compaction roller affected the degree of compaction, but the direction of compaction did not. Therefore, if the compaction work is performed by adjusting the driving speed and vibration method of the vibrating roller according to the ground conditions, repetitive compaction work can be reduced, thereby reducing construction costs and lowering work time, which will achieve an improved work efficiency.

1. Introduction

Road compaction is one of the most critical steps to ensuring road quality and longevity in all stages of road construction. However, quality measurement after conventional compaction work has low accuracy due to the limitations of the one-point test method, leading to a decrease in road quality. Notably, the inefficiency of repeated construction and inspection processes when constructing roads or complexes must be addressed. Checking the quality of each section using manpower would be almost impossible. Additionally, the accuracy would be low and the process would take too much time. For this reason, it is necessary to develop automated quality monitoring technologies to solve these problems. Repeated compaction is essential to obtain the compaction quality required after embankment in road construction.

Soil compaction rollers are machines that apply a force (such as vibration or impact) to soil or crushed stone with voids to increase its bearing capacity. They are used in the construction of roads and foundations, to compact soil, gravel, or concrete. In general, vibratory rollers are the type most frequently used in road construction, and the compaction work is performed by attaching a starter to the front or rear wheel and applying its weight and vibration by vibrating the iron wheel. Compaction is usually performed back and forth at approximately 2–4 km/hr. There are two vibration methods: vibration and oscillation.

The plate load test (PLT) and field density test (FDT) are currently the most commonly used compaction quality inspections after embankment in the civil engineering works. These testing methods rely on operator judgment when determining the test positions, and the accuracy of the results varies depending on their proficiency. For this reason, it is impossible to quantitatively verify the results of compaction work using current testing methods. Also, quality inspections cannot be performed in all sections due to cost and time. To overcome these limitations, intelligent quality control techniques for compaction work are being developed [1–3]. Over the past 30 years, research has been conducted on continuous compaction control (CCC), mainly in the US and Europe. CCC systems allow engineers to simultaneously assess the compaction achieved while performing compaction work in the field [4–8]. In the United States, IC technologies have begun to be used in highway construction, with the TH-64 reconstruction project in Minnesota recognized as the first project to require IC technologies [9]. Many states also apply IC technologies for QC (quality control)/QA (quality assurance) [2, 8, 10, 11]. The compaction equipment used in CCC is a system that measures ground stiffness based on the relationship between the vibration applied to the compaction roller and the ground response (repulsive force) caused by it by attaching various sensors to the compaction roller. Rollers equipped with such CCC technologies are called IC rollers, and many specification standards for IC rollers have already been proposed in other countries [12, 13]. Today, in many countries, including the United States, Japan, and Germany, compaction roller manufacturers sell compaction rollers with CCC systems. As discussed above, many countries use intelligent compaction, and research on the related technologies has also been conducted in Korea. There is also a case where this technology has been applied to a highway construction site in Korea. Looking at the results of tests performed at actual highway construction sites, it was found that the compaction quality varied depending on the operating conditions of the compaction roller during compaction work. The degree of ground compaction is influenced by the compaction operator's driving technique, the roller's speed, the moving direction of the roller, and the method of compaction. Moreover, since not many manuals provide accurate information on how to perform compaction work, including compaction speed and vibration method, most people rely on their own experience and judgment for the task. To address this issue, the present study conducted a field test using a roller equipped with an intelligent compaction control system. The purpose was to investigate how the compaction speed, vibration method, and roller's direction affect the intelligent compaction value and to suggest appropriate speed and vibration methods for field compaction work. By utilizing this approach and applying suitable compaction speed and vibration method during road construction, various benefits can be expected, including a shortened construction period, reduced construction costs, and prevention of pothole accidents.

2. Factors of the Roller Operation Method Influencing Soil Stiffness

2.1. Intelligent Compaction Control System. As shown in Figure 1, an IC roller is a conventional compaction roller equipped with

FIGURE 1: An intelligent roller equipped with a tablet, GPS sensor, and accelerometer.

an accelerometer, GPS sensor, and a tablet computer. It can acquire and visualize data in real time by continuously assessing the degree of compaction. This system allows us to control the number of compactions and the quality of all areas of compaction work.

The CMV (compaction meter value) can be obtained using the continuous compaction evaluation method, and is calculated as the ratio of the first harmonic amplitude to the fundamental frequency amplitude by analyzing the acceleration measured over time while the vibratory roller is operating (Figure 2). Previous research has proposed that CMV can be expressed as in Equation (1) [5, 14, 15].

$$\mathrm{CMV} = \mathrm{C}\frac{A_{2\Omega}}{A_{\Omega}}, \quad (1)$$

(C = constant (300 is commonly used as a constant related to the ground), A_{Ω} = acceleration amplitude of the first harmonic component, $A_{2\Omega}$ = acceleration amplitude of the fundamental frequency component)

where, C is a constant with a typical value of 300, which was also used in this study.

2.2. Vibratory Roller Direction. Even if compaction work is performed under the same ground conditions, compaction is often lower when the compaction roller is operated in reverse. However, as shown in Figure 3, from the perspective of the kinematic mechanism of the compaction rollers, there should be no difference depending on the roller's direction if conditions, such as the traveling speed and the ground conditions, are the same when the compaction roller moves forward/backward. For this reason, field tests were conducted to investigate how the degree of compaction changes depending on the vibratory roller's traveling direction.

2.3. Vibratory Roller Speed. The compaction roller has a running speed of up to 10 km/hr. This is utilized when moving the compaction roller, and compaction is typically performed at a speed of 2 km/hr. In the field, compaction work may be performed at a higher speed of up to 4 km/hr depending on the worker. Therefore, in order to determine how the degree of compaction changes according to the speed of the compaction roller, the experiment was conducted by dividing the

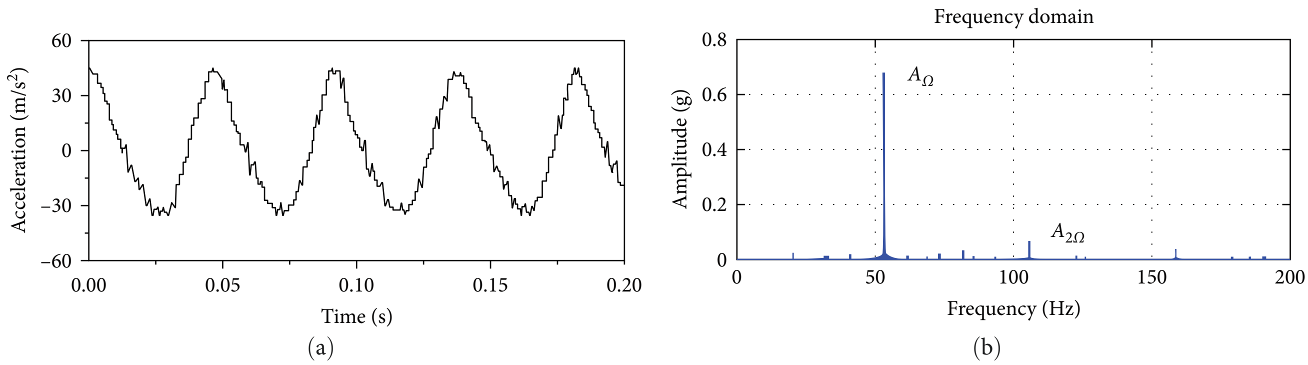

Figure 2: Method to determine CMV (pass 1, for example): (a) acceleration time history of roldrum and (b) acceleration frequency spectra of roller drum [5, 14, 15].

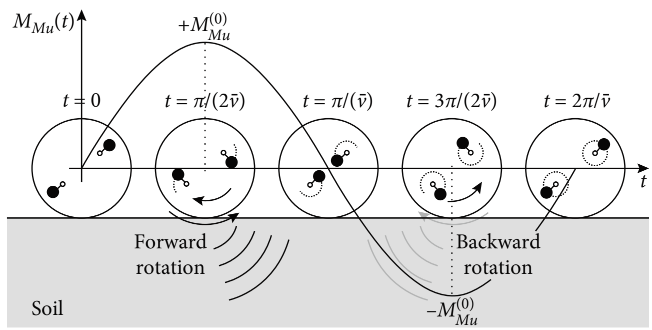

Figure 3: Excitation torque MMu(t) in an oscillation drum and corresponding location of the unbalance at discrete time instants, based on [16].

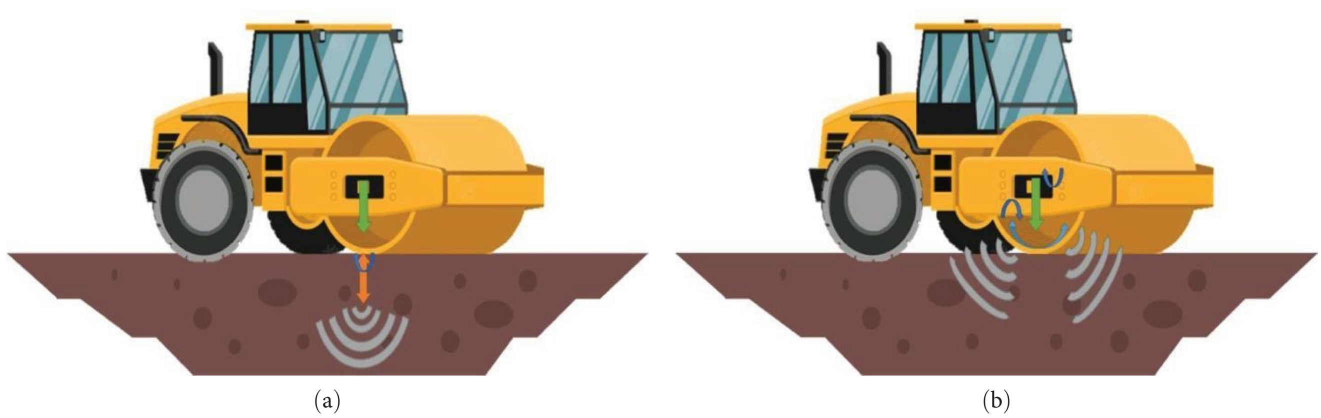

Figure 4: Forces and moments of dynamic drums: vibrating drum (a) and oscillating drum (b) [17].

speed into two types. This study conducted an experiment to see how the degree of compaction changes when compaction was performed at 2 and 4 km/hr.

2.4. Vibration Method (Vibration and Oscillation). Vibratory rollers currently on the market allow the operator to select the vibrating method according to field conditions. As shown in Figure 4, compaction methods can be divided into two main types: vibrating drum (a) and oscillating drum (b) [17]. A vibrating drum generates alternating upward–downward motions by rotating a single unbalanced mass on the drum's axis. An oscillating drum has two masses (two unbalanced masses or two opposite eccentric masses) arranged eccentrically to the drum's axis, which rotate synchronously in the same direction. This creates an alternating high-frequency forward–backward motion of the drum. This study conducted tests to examine how the vibration method affects the degree of compaction.

3. Actual Highway Construction Site Test Results

3.1. Field Test Overview. The field test location is the Anseong–Yongin Expressway in Gyeonggi-do, Korea, and the test was conducted in the road body construction section for the expressway. On the test site (raw ground and underlying

Table 1: Field sample properties.

USCS	PI	Gs	D30 (mm)	D50 (mm)	D60 (mm)	γd (max) (t/m_3)	ω opt (%)
SP-SM	N.P	2.65	0.38	1.45	2.50	1.96	8.6

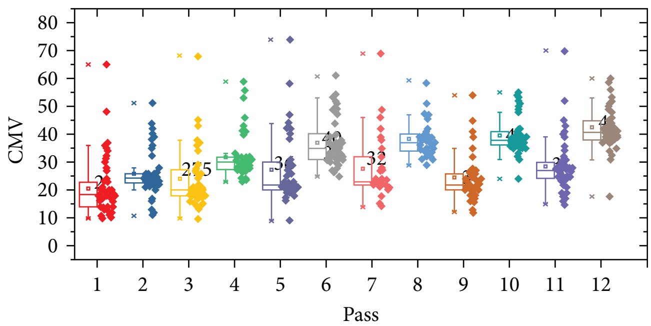

Figure 5: Distribution of CMV by number of roller pass.

layer) with a length and width of 30 and 3 m, respectively, the embankment material was laid to a thickness of about 500 mm. After laying, test construction (compacting) was performed using a cylindrical roller. An accelerometer was installed on the roller to derive an intelligent compaction value (CMV), and compaction characteristics (number of compactions and speed) were measured from location information using a GPS sensor. Table 1 shows the basic property values of the embankment materials from laboratory tests.

The amount of the embankment material passing through a No. 4 sieve and a No. 200 sieve was 69.7% and 12.1%, respectively. The plasticity index showed NP and was classified as SM (silty sand) according to the unified soil classification system (USCS). The maximum dry unit weight and optimum water content ratio are 1.96 t/m^3 and 8.6%, respectively. It was found that compaction could satisfy 95% of the maximum dry unit weight in the range of 5.3%–12.5% water content. Compaction was performed 12 times (one way), and the test was conducted in the forward direction for odd compactions and in the backward direction for even compactions, respectively. The compaction roller used during the test was a Bomag BW 211D roller. The diameter and width of the drum are 1.5 and 2.13 m, respectively, the total weight is 10,600 kg, and the drum load is 5,670 kg. The excitation frequency of the roller is about 30–34 Hz. Figure 5 shows the CMV results by the number of compactions.

A method was used to increase the precision and reliability of the CMV value using raw data to obtain the representative CMV. Data within a normal distribution, which is the most commonly used statistical processing method, were extracted. Figure 6 shows the representative CMV values for each compaction number by extracting the mean value.

As shown in Figure 2, the experiment results showed that the CMV of odd-numbered compactions was distributed lower than that of even-numbered compactions. The reason for this was that the speed of the roller during compaction was adjusted to about 4 km/hr in odd-numbered compactions (roller forward) and about 2 km/hr in even-numbered compactions (roller backward). This is thought to be because

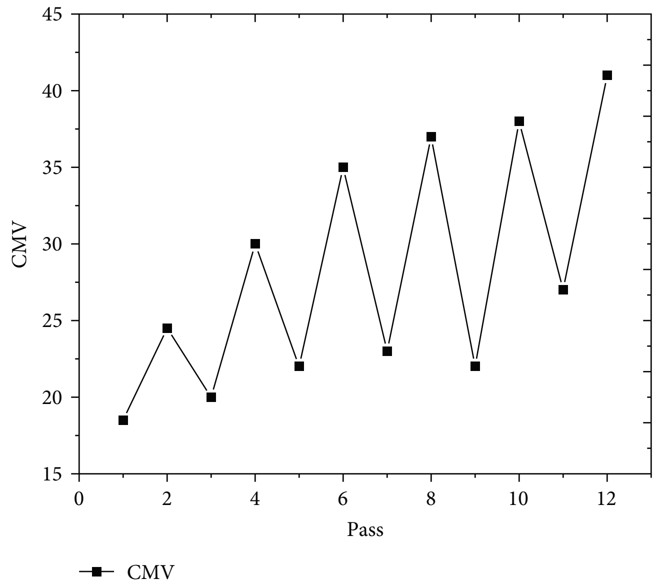

Figure 6: Median CMV by number of roller pass.

Figure 7: Field test site (social demonstration center).

roller operators typically run slower to ensure visibility when reversing. According to Adam [18], the slower the roller's working speed, the higher the roller's compression rate. In addition, Pistrol et al. [19] reported that the effect of speed is greater when the mode of the roller is vibration than when the compaction speed is slow. Therefore, this study conducted a full-scale pilot test to determine how these influencing factors affect the degree of compaction.

4. Field Test Method and Conditions

4.1. Field Test Overview. In this study, a full-scale site was constructed to replicate real-life conditions, and weathered granite soil, commonly used in actual road construction sites, was utilized as the ground material. The test method involved three variables (compactor roller speed, vibration method, and compaction direction) that were tested. To assess the

Table 2: Field test method.

No	Velocity (km/hr)	Direction	Vibration method
1	2	Forward	Oscillation
2	2	Forward	Vibration
3	4	Forward	Oscillation
4	4	Forward	Vibration
5	2	Backward	Vibration
6	2	Backward	Oscillation

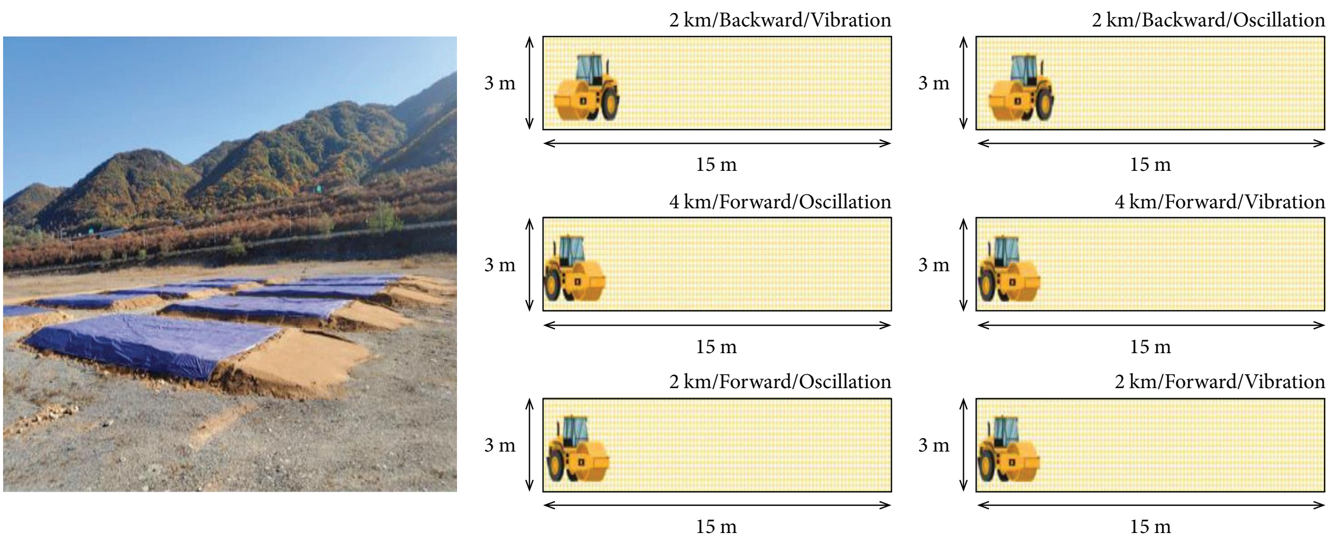

Figure 8: View of test site and compaction test section size.

Table 3: Field sample properties.

USCS	PI	G_s	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	R_{dmax} (t/m^3)	W_{opt} (%)
SP-SM	N.P	2.65	9.8	71.4	13.4	4.5	1.93	9.9

compaction level of the entire section, an intelligent quality management system was utilized to obtain the CMV values. The obtained CMV values from the entire section were analyzed using the median value as a representative indicator of the compaction level. Figure 7 shows the test site, where a test bed was created at the Yeoncheon SOC Demonstration Research Center of the Korea Institute of Civil Engineering and Building Technology. The center is located in Yeoncheon-gun, Gyeonggi-do.

Table 2 shows the test conditions, which consist of three variables. The first variable was speed (2 and 4 km/hr), the second was the roller travel direction (forward and backward), and the last was the vibration method, divided into oscillation and vibration.

4.2. Field Test Conditions and System. As shown in Figure 8, a test bed was created at the Yeoncheon SOC Demonstration Research Center to perform the field tests. Earth and sand were laid on the original ground to form six lanes. The size of each lane was 3 m wide and 15 m long. Tarps were placed on top of the soil to control the moisture content of the ground.

Table 3 shows the grain size test results of the embankment materials obtained from indoor tests. From the D compaction test of the test method for soil compaction in a laboratory [20], the maximum dry density (1.928 t/m^3) and the optimum water content (9.9%) satisfied the quality standards for roadbed soil pile materials (Figures 9 and 10).

5. Field Test Results

In the field test, 10 compaction cycles were performed in all lanes, and data were acquired by time-synchronizing one location data and CMV value per second through the GPS sensor. Even if the test material is suitable for embankment work, there is heterogeneity in the material itself. Also, since the CMV influence depth includes up to 1.5 m of the subsurface depth, the CMV may vary depending on the strength of the original ground. The representative value for each compaction cycle was calculated by statistically processing the raw data for each cycle and removing the outliers from the normal distribution to analyze the CMV results according to each influencing factor.

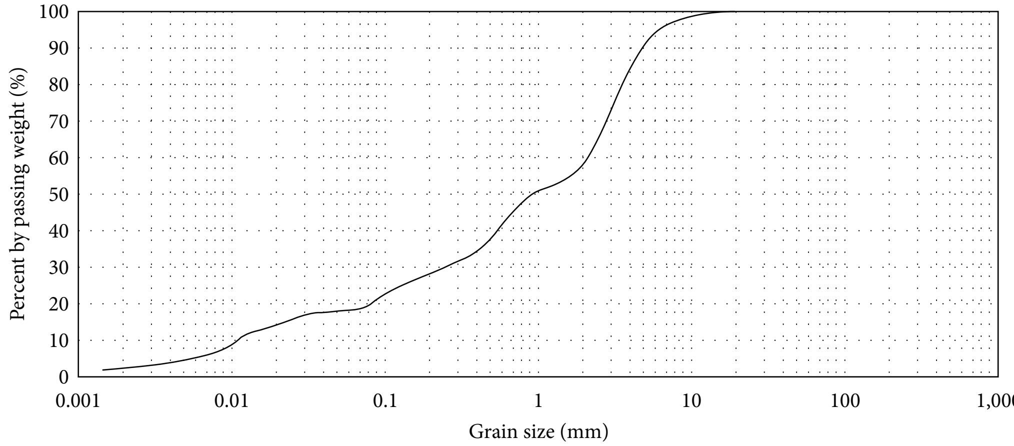

Figure 9: Grain size distribution curve of soil used in the field.

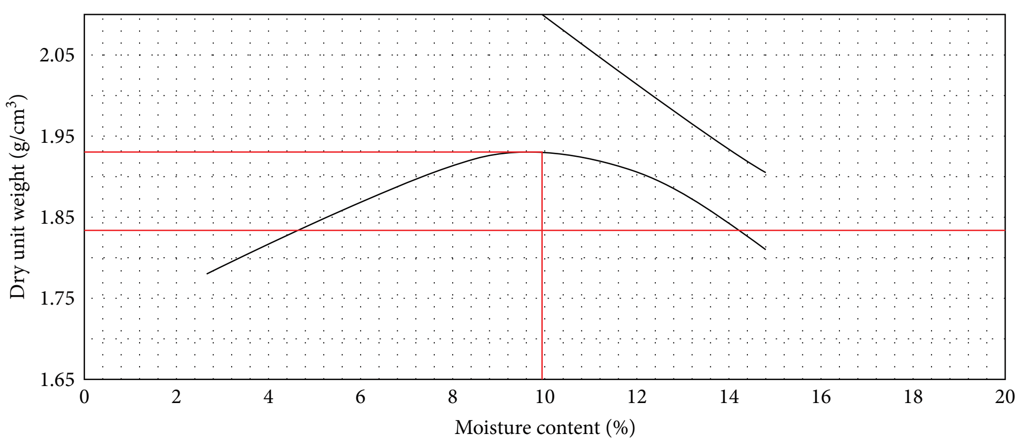

Figure 10: Optimal moisture content and dry density of soil used in the field.

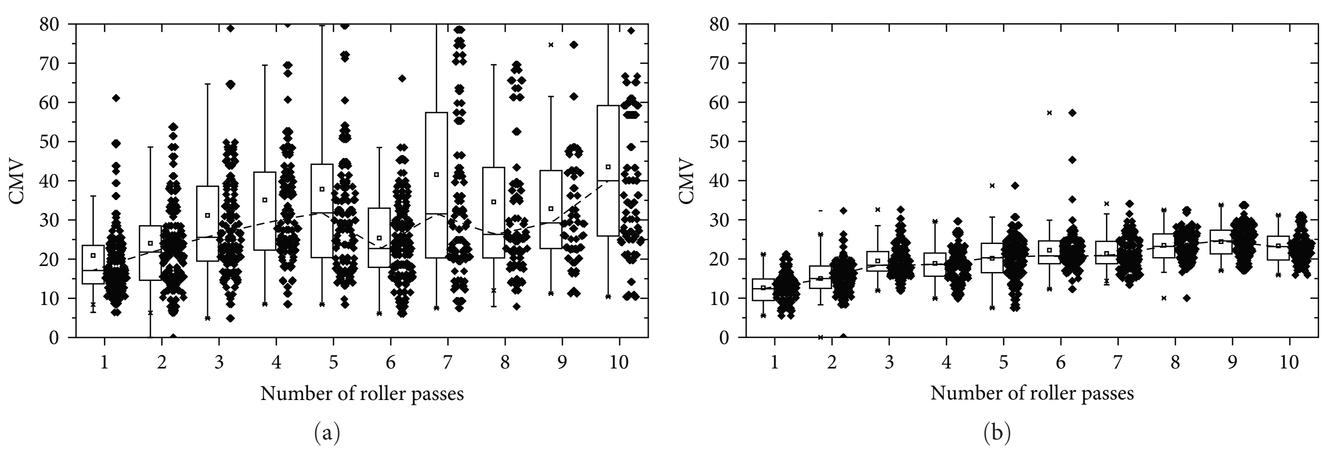

Figure 11: Forces and moments of dynamic drums: (a) vibrating drum (2 km, forward, vibration) and (b) oscillating drum (4 km, forward, vibration).

5.1. Vibratory Roller Speed. According to Adam [18], the slower the roller travels, the higher the roller's compaction efficiency. Increasing the compaction roller's speed reduces the efficiency of compaction energy, resulting in a relatively low-compaction density. In the field test, compaction tests were performed at 2 and 4 km/hr to examine the effect of the compaction roller's speed. Figure 11 shows the CMV distribution according to speed for each number of compactions.

When fitting using the median for each number of compactions, as shown in Figure 12, the faster the compaction speed, the lower the CMV. These results show that the degree of compaction changes depending on the speed difference.

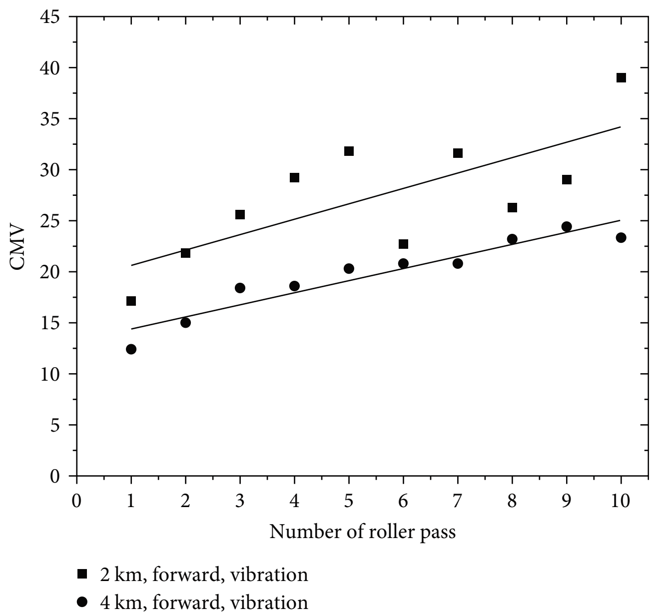

Figure 12: Normalized CMV value as a function of the speed of the vibrating roller.

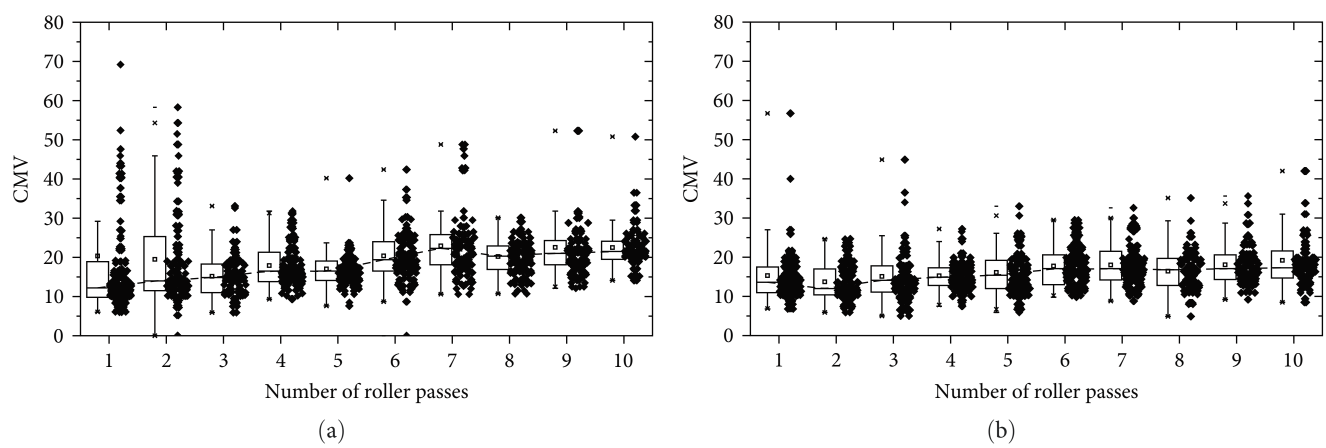

Figure 13: CMV result according to the direction of the vibrating roller: (a) 2 km, forward, oscillation and (b). 2 km, backward, oscillation.

5.2. Vibratory Roller Direction. Compaction work was performed in one direction (moving forward and backward) under the same conditions (vibration method: oscillation, compaction roller speed: 2 km/hr) to examine the degree of compaction according to the vibratory roller's direction. Figure 13 shows the CMV distribution according to the direction of the compaction roller for each number of compactions.

When fitting using the median for each number of compactions, as shown in Figure 14, there is no significant difference between the CMV results when the compaction roller is moving forward/backward, indicating that moving the roller forward/backward has an insignificant effect on compaction. The degree of compaction is generally lower in reverse gear because the operator tends to work at slower speeds due to reduced visibility.

However, as shown in Figure 15, if the shape of the settlement trough changes according to the ground conditions, there may be differences in the degree of compaction according to whether the roller is moving forward/backward due to different forces being applied to the ground.

5.3. Vibration Method. Field tests were conducted to evaluate the impact of the vibration method on compression. Ground conditions and water content were the same, the roller vibration speed was 2 km/hr, and the roller travel direction was the same as in the forward test. Figure 16 shows the CMV distribution according to the vibration method (a) and vibration (b) according to the number of compactions.

Vibrating drums generate alternating upward–downward motions of the drum by rotating a single unbalanced mass placed on the drum's axis. Oscillating drums have two masses arranged eccentrically to the drum's axis, which rotate synchronously in the same direction. It works on the principle of alternately generating high frequency, forward–backward motion of the drum.

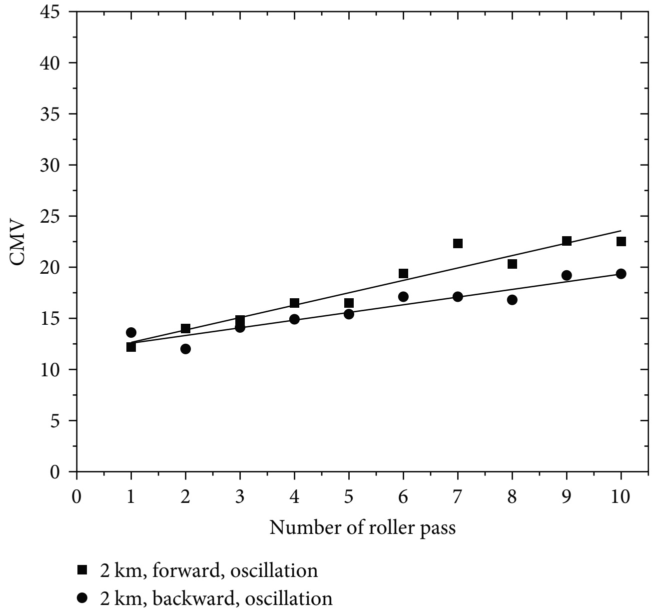

Figure 14: Normalized CMV value according to the direction of travel of the vibrating roller.

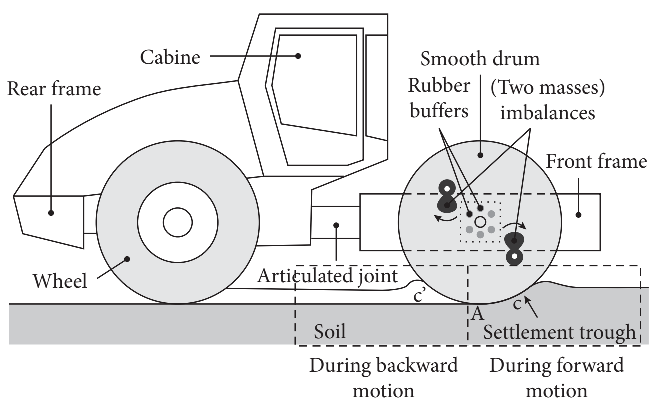

Figure 15: Settlement trough shape according to the direction of the compaction roller [16].

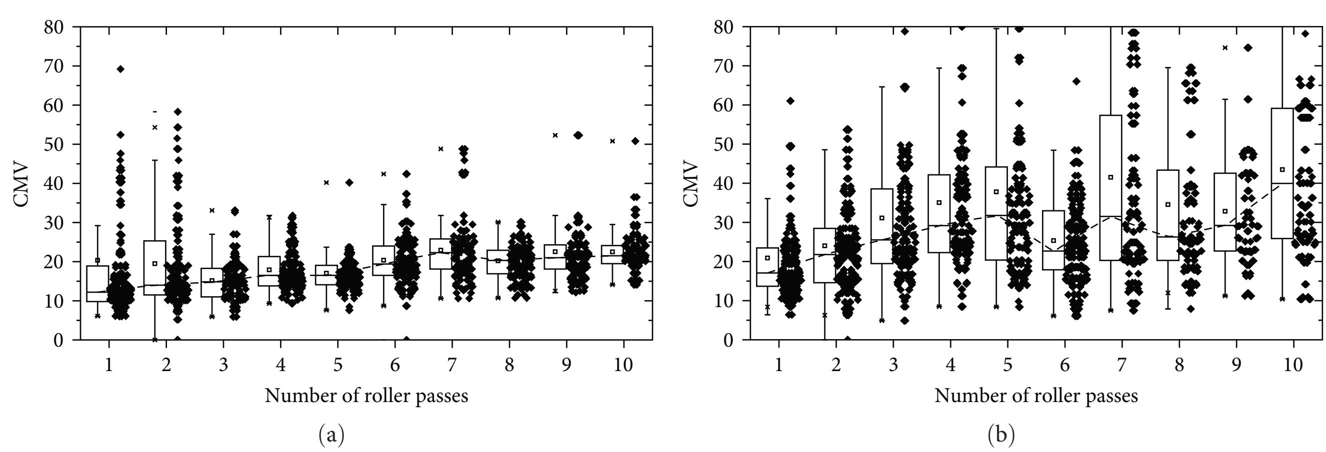

Figure 16: Settlement trough shape according to the direction of the compaction roller: (a). 2 km, forward, oscillation and (b) 2 km, forward, vibration.

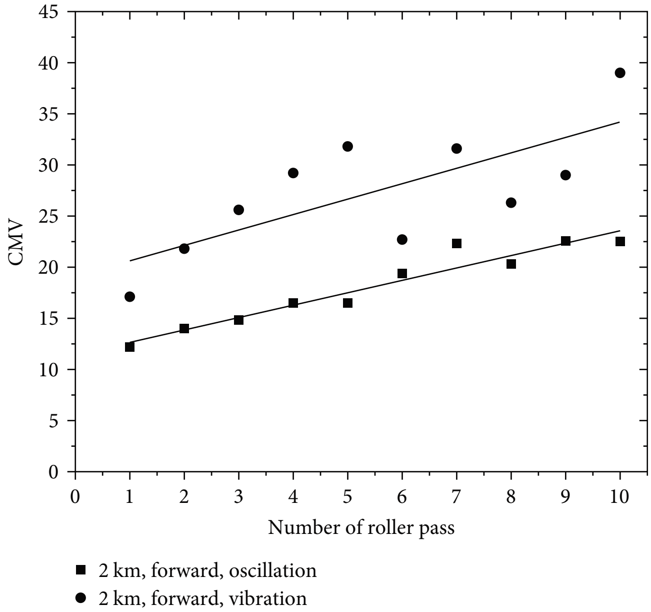

Figure 17: Normalized CMV values according to the vibration method.

As shown in Figure 17, when fitting using the median for each number of compactions, the results of performing compaction work with both vibration methods show that the CMV is higher when using a vibration drum that generates alternating up–down motions.

6. Conclusions

This study used an intelligent quality control system capable of inspecting quality in all compaction areas to investigate how the degree of compaction changes depending on the compaction roller's operating conditions. Field tests were conducted at the Yeoncheon SOC Demonstration Research Center of the Korea Institute of Civil Engineering and Building Technology. Full-scale road embankment sections were simulated using road embankment materials. The field tests were also conducted with the same equipment as the ground material in all sections. The compaction roller's traveling direction, speed, and vibration method were set as the field test variables. According to the test results, the average difference in CMV results according to speed was 7.685, the average difference in CMV results according to the roller's direction was 2.155, and the average difference in CMV results according to the compaction roller's vibration method was 9.301. The vibration method and roller speed affected ground compaction by about 20%–30% more than the roller's direction, while the travel direction had no significant effect. The results of this study can be utilized in real-world compaction operations. By utilizing a roller equipped with an intelligent compaction control system, operators can set and adjust the appropriate compaction speed and vibration method, thereby enhancing construction quality and reducing construction time. Consequently, construction costs can be reduced as well. Furthermore, unnecessary issues such as pothole accidents can be prevented, and the overall durability and safety of roads can be improved.

The main findings are as follows:

(1) The results of tests that involved controlling the compaction roller's speed (2 and 4 km/hr) showed that the vibratory roller's speed affects the degree of compaction. The degree of compaction was lower when the roller's speed was 4 km/hr, indicating that the higher the speed of the vibratory roller, the less the compaction effect of the ground. Therefore, it is necessary to observe the speed of the compaction roller according to field conditions.

(2) The results of testing the compaction roller in both forward and backward directions showed no significant effect between the compaction roller's traveling direction and the degree of compaction. In general, the compaction roller tends to move slower in reverse than forward, so the degree of compaction tends to be lower during reverse operations. However, if the shape of the settlement trough changes, there may be differences in the degree of compaction according to whether the roller is moving forward/backward.

(3) Vibratory rollers usually have two main controllable vibration methods: oscillation and vibration. The analysis results using CMV showed that vibration has a larger CMV, confirming it has a greater compaction effect on granite-weathered soil, a common embankment material. Therefore, it is necessary to control the vibration method according to the field conditions.

This study was conducted under the specific ground conditions; therefore, caution is required when applying these results to different ground conditions. Thus, further research is necessary to consider specific ground conditions and investigate the compaction roller's speed and vibration method for each situation. Additionally, it should be noted that the analysis in this study is based on experimental data, which may not fully account for all variables and uncertainties present in real-world scenarios. Hence, when considering the applicability of these findings in actual field situations, comprehensive and realistic field tests and experiences should be taken into account.

Data Availability

The data that support the findings of this study are available from the Korea Institute of Civil Engineering and Building Technology, but the availability of these data, which were used under license for the current study, is limited, and thus they are not publicly available. Data are, however, available from the orresponding author upon reasonable request and with permission from the Korea Institute of Civil Engineering and Building Technology.

Disclosure

The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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