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# Investigation on Characteristics of Intelligent Compaction Measurement Value (ICMV) Based on Meta-Analysis

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## ABSTRACT

Intelligent Compaction Measurement Value (ICMV) is a real-time and continuous compaction quality information obtained from sensors attached to a compaction roller. Despite the numerous advantages of intelligent compaction, its practical application in earthwork quality control has been limited. This can be attributed to the lack of a substantial track record to replace traditional field quality testing methods and a general lack of understanding regarding ICMV. In this study, we collected 12 literature sources that implemented intelligent compaction technology in field applications; a meta-database consisting of 1,206 ICMV-FTV data pairs was constructed. Using the metadata, the correlation between ICMV and FTV was evaluated using a simple linear regression analysis. The results of this study can serve as fundamental data for determining the target ICMV and developing the quality control guidelines for subgrade base based on intelligent compaction

## 1. INTRODUCTION

During earthwork operations, it is crucial to properly compact the fill material (soil). Insufficient soil compaction can result in reduced strength and excessive settlement, leading to increased maintenance costs for infrastructure (KICT, 2018). Traditionally, vibratory rollers are used for soil compaction at earthwork sites. After the compaction process, the quality of the compacted soil is assessed through various field tests, including plate load tests (PLT), field density tests (FDT), dynamic cone penetration tests (DCPT), and light weight deflectometer tests (LWDT). However, these field tests have limitations as they assess soil properties only at the specific locations and are conducted in a limited number of areas due to time and cost constraints. Therefore, ensuring consistent compaction quality across the entire earthwork site poses a challenge.

Furthermore, the current compaction process relies on the expertise of the roller operator. While the operator's experience is valuable, the quality of the soil compaction can vary depending on their skill level. It is challenging for the operator to accurately determine the optimal number of roller passes for different areas of the fill material,

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leading to sections that are either over-compacted or under-compacted. Consequently, the existing compaction process does not allow for a comprehensive quality control of the fill material and optimized compaction efforts.

Intelligent compaction (IC) has emerged as a method to achieve the desired level of quality in asphaltic or soil layers by monitoring and controlling roller parameters to optimize the compaction effort (Cai et al., 2017). In Fig. 1, an IC device is illustrated, which includes high-precision GPS and roller-integrated soil response sensors attached to the compaction roller. This IC management device enables real-time monitoring of the number of roller passes and captures the Intelligent Compaction Measurement Value (ICMV). Here, ICMV represents a compaction-related index derived from continuously acquired measurement values through sensors attached to the compaction roller, enabling comprehensive compaction process management and continuous assessment of the compaction quality.

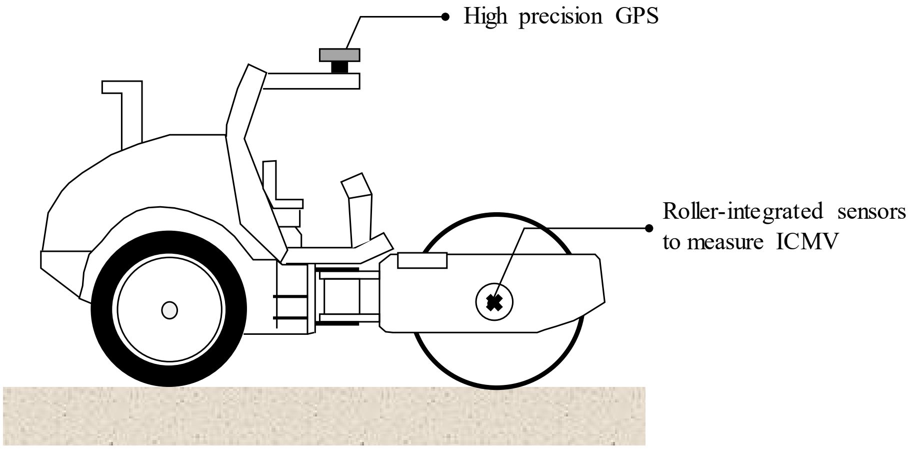


Fig. 1 Key features of intelligent compaction (IC) roller.

Despite the numerous advantages of intelligent compaction, there are limited cases where ICMV has been applied in actual earthwork quality control. This can be attributed to the lack of a sufficient track record to replace traditional field quality testing methods and a general lack of understanding of ICMV (Baek et al., 2020). The successful implementation of intelligent compaction in earthwork construction practice requires knowledge of ICMV and their relationships with the results of the field tests, referred to as "field test value (FTV)", which can be used for earthwork quality control (White et al., 2007). However, acquiring a significant number of data pairs of ICMV and FTV is challenging due to the limited number of cases applying intelligent compaction.

To address this, we collected 12 documents (field reports and research papers) investigating intelligent compaction technology in the field; a meta-database consisting of 17 IDs and 1,206 ICMV-FTV data pairs was constructed. Using the metadata, the correlation between ICMV and FTV was evaluated using a simple linear regression analysis. The results of this study can serve as fundamental data for determining the target ICMV and developing the quality control guidelines for subgrade base based on intelligent compaction.

## 2. MATA-DATABASE FOR ICMV and FTV

### *2.1 Existing literatures related to intelligent compaction technology*

The research on compaction quality control using ICMV originated from the field application of vibratory rollers with accelerometer attachments by the Swedish Highway Administration in 1974 (Thurner and Sandstrom, 2000). Subsequently, a number of field studies in various states of the United States were conducted by Professor D. J. White. In Korea, there were attempts to introduce intelligent compaction technology, which evaluates compaction quality continuously based on roller-integrated sensors, by the Road Construction Authority in the early 2000s. However, these efforts were not sustained. More recently, research has been conducted to implement intelligent compaction in response to the demand for construction automation. Baek et al. (2020) conducted fundamental research on using intelligent compaction technology for earthwork quality control, and a standard specification for intelligent compaction (KCS 10 70 20: 2021) was established to facilitate its practical implementation. Nevertheless, there have been no reported cases of compaction quality control based on ICMV in real-world field applications.

Table 1 provides a comprehensive overview of 12 reports and papers that conducted field tests on the application of intelligent compaction. These studies covered a wide range of fill materials including GW (well-graded gravel), GP (poorly-graded gravel), GM (gravel with silt), GC (gravel with clay), SW (well-graded sand), SM (sand with silt), ML (low plasticity silt), and CL (low plasticity clay).

Table 1 Key features of intelligent compaction (IC) roller

| Researcher | Soil Type | Roller Manufacturer | ICMV | FTV* |
|---|---|---|---|---|
| Forssblad (1980) | GW | Dynapac | CMV | PLT, FWDT |
| Hansbo and Pramborg (1980) | SW, SM, ML | Dynapac | CMV | Sand cone, PLT, CPT, DCPT |
| Floss et al. (1983) | GM | Dynapac | CMV | Sand cone, PLT, DCPT |
| Petersen and Peterson (2006) | ML | Caterpillar | CMV | LWDT, DCPT, SSG |
| White et al. (2007a) | CL, GM, GP, SM, GC | Caterpillar | CMV, MDP | PLT, NG, DCPT, LWDT, CIH |
| White et al. (2007b) | SW-SM, SP-SM, CL | Caterpillar, Ammann | CMV, $k_s$, MDP, CCV | NG, DCPT, LWDT, SSG, CIH |
| White et al. (2008) | GP-GM, SM, CL | Dynapac, Ammann | CMV, $k_s$ | PLT, FWDT, LWDT, SSG, CBR, |
| White and Thompson (2008) | CL | Caterpillar | CMV, MDP | NG, DCPT, LWDT, CIH |
| White et al. (2009a) | GW, SM | Caterpillar, Bomag | CMV, MDP | PLT, NG, DCPT, LWDT, SDG |
| White et al. (2009b) | SP-SM, SM | Caterpillar, Ammann, Sakai | CMV, $k_s$, CCV | PLT, NG, LWDT, DCPT, FWDT, |

| | | | | |
|---|---|---|---|---|
| Meehan et al. (2017) | SM | Caterpillar | CMV, MDP | NG, SSG, LWDT, DCPT |
| Cai et al. (2017) | ML | Caterpillar | CMV, MDP | DCPT, LWDT, FWDT |

[*] PLT: Plate Load Test, NG: Nuclear Gauge, SSG: Soil Stiffness Gauge, SDG: Soil Density Gauge, CIH: Clegg Impact Hammer, FWDT: Falling Weight Deflectometer Test, DCPT: Dynamic Cone Penetrometer Test, LWDT: Light Weight Deflectometer Test.

These studies utilized vibratory rollers from manufacturers such as Caterpillar, Sakai, Ammann, and Bomag, equipped with IC devices. During the compaction process, various ICMV values, including Compaction Meter Value (CMV), Machine Driving Power (MDP), and Roller-integrated Stiffness ($k_s$), were measured. Also, field tests such as PLT, NG, SSG, SDG, CIH, FWDT, DCPT, and LWDT were conducted to obtain FTV before and after the compaction process. The distribution of ICMV and FTV data was presented for each testbed. GPS technology was utilized to collect ICMV data at the same location as the field tests, allowing for the establishment of data pairs (ICMV and FTV). Regression analysis was conducted to evaluate the correlation between each ICMV and FTV.

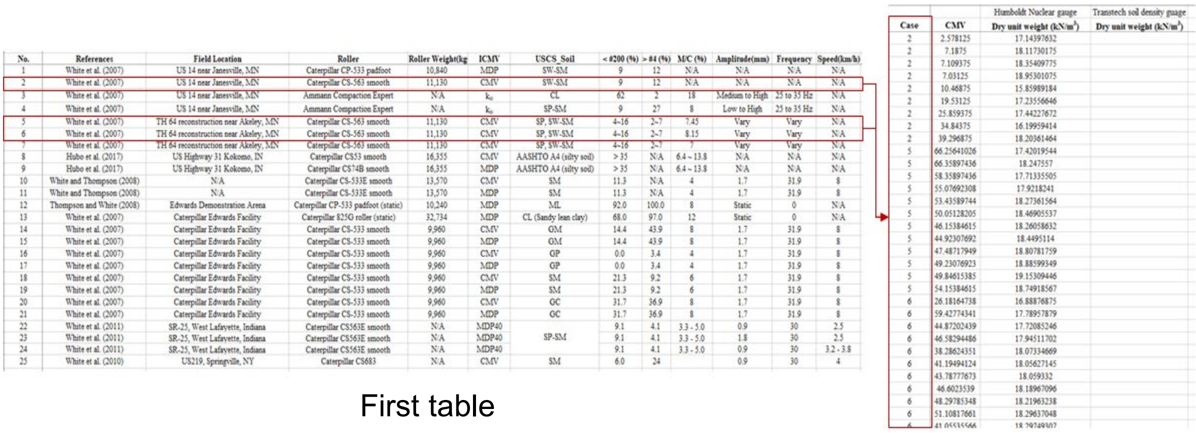
### *2.2 Construction of meta-database for ICMV and FTV*

To utilize intelligent compaction for earthwork quality control, establishing the correlation between ICMV and FTV is crucial. This requires the accumulation of a substantial amount of ICMV-FTV data from field tests. In this study, we collected data from various existing literature sources that included CMV, PLT, NG, LWDT, CIH, and DCPT results (i.e., CMV-FTV data pairs), providing provided diverse sets of ICMV-FTV data. The graphical representations of the ICMV-FTV data from these literature sources were digitized using the open-source software WebPlotDigitizer ver 4.6, enabling the conversion of the data into numerical values. Through this digitization process, we obtained a total of 1,206 digitized CMV-FTV data pairs, as summarized in Table 2.

Table 2 The number of CMV and FTV data pairs collected in this study

| ICMV | PLT | NG | LWDT | | | CIH | | DCPT | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | $E_v$ | $\gamma_d$ | $E_{LWD-K3}$ | $E_{LWD-z2}$ | $E_{LWD-z3}$ | $CIV_{4.5kg}$ | $CIV_{20kg}$ | DPI | CBR | |
| CMV | 35 | 222 | 125 | 103 | 75 | 131 | 57 | 211 | 245 | 1,206 |

These data pairs were organized into a relational database implemented in an Excel file (Fig. 2). The first table of the relational database contained information about the data source, field location, roller information, fill material type, operating conditions of the roller, and a list of FTV. Each attribute was arranged in columns, and a unique ID (number) was assigned to each record in separate rows. When there was an expectation of significant variations in the intelligent compaction information across different attributes, distinct IDs were assigned. Starting from the second table, the first column represented the ID, and the digitized data were recorded from the second column onwards. Consequently, we constructed a meta-database comprising 17 IDs and 1,206 ICMV-FTV data pairs.



| No. | References | Field Location | Roller | Roller Weight(kg | ICMV | USCS_Soil | < #200 (%) | > #4 (%) | M/C (%) | Amplitude(mm) | Frequency | Speed(km/h) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | White et al. (2007) | US 14 near Janesville, MN | Caterpillar CP-533 padfoot | 10,840 | MDP | SW-SM | 9 | 12 | N/A | N/A | N/A | N/A |
| 2 | White et al. (2007) | US 14 near Janesville, MN | Caterpillar CS-563 smooth | 11,130 | CMV | SW-SM | 9 | 12 | N/A | N/A | N/A | N/A |
| 3 | White et al. (2007) | US 14 near Janesville, MN | Ammann Compaction Expert | N/A | $k_s$ | CL | 62 | 2 | 18 | Medium to High | 25 to 35 Hz | N/A |
| 4 | White et al. (2007) | US 14 near Janesville, MN | Ammann Compaction Expert | N/A | $k_s$ | SP-SM | 9 | 27 | 8 | Low to High | 25 to 35 Hz | N/A |
| 5 | White et al. (2007) | TH 64 reconstruction near Akeley, MN | Caterpillar CS-563 smooth | 11,130 | CMV | SP, SW-SM | 4~16 | 2~7 | 7.45 | Vary | Vary | N/A |
| 6 | White et al. (2007) | TH 64 reconstruction near Akeley, MN | Caterpillar CS-563 smooth | 11,130 | CMV | SP, SW-SM | 4~16 | 2~7 | 8.15 | Vary | Vary | N/A |
| 7 | White et al. (2007) | TH 64 reconstruction near Akeley, MN | Caterpillar CS-563 smooth | 11,130 | CMV | SP, SW-SM | 4~16 | 2~7 | 7 | Vary | Vary | N/A |
| 8 | Hubo et al. (2017) | US Highway 31 Kokomo, IN | Caterpillar CS53 smooth | 16,355 | CMV | AASHTO A4 (silty soil) | > 35 | N/A | 6.4 ~ 13.8 | N/A | N/A | N/A |
| 9 | Hubo et al. (2017) | US Highway 31 Kokomo, IN | Caterpillar CS74B smooth | 16,355 | MDP | AASHTO A4 (silty soil) | > 35 | N/A | 6.4 ~ 13.8 | N/A | N/A | N/A |
| 10 | White and Thompson (2008) | N/A | Caterpillar CS-533E smooth | 13,570 | CMV | SM | 11.3 | N/A | 4 | 1.7 | 31.9 | 8 |
| 11 | White and Thompson (2008) | N/A | Caterpillar CS-533E smooth | 13,570 | MDP | SM | 11.3 | N/A | 4 | 1.7 | 31.9 | 8 |
| 12 | Thompson and White (2008) | Edwards Demonstration Arena | Caterpillar CP-533 padfoot (static) | 10,240 | MDP | ML | 92.0 | 100.0 | 8 | Static | 0 | N/A |
| 13 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar 825G roller (static) | 32,734 | MDP | CL (Sandy lean clay) | 68.0 | 97.0 | 12 | Static | 0 | N/A |
| 14 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | CMV | GM | 14.4 | 43.9 | 8 | 1.7 | 31.9 | 8 |
| 15 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | MDP | GM | 14.4 | 43.9 | 8 | 1.7 | 31.9 | 8 |
| 16 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | CMV | GP | 0.0 | 3.4 | 4 | 1.7 | 31.9 | 8 |
| 17 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | MDP | GP | 0.0 | 3.4 | 4 | 1.7 | 31.9 | 8 |
| 18 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | CMV | SM | 21.3 | 9.2 | 6 | 1.7 | 31.9 | 8 |
| 19 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | MDP | SM | 21.3 | 9.2 | 6 | 1.7 | 31.9 | 8 |
| 20 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | CMV | GC | 31.7 | 36.9 | 8 | 1.7 | 31.9 | 8 |
| 21 | White et al. (2007) | Caterpillar Edwards Facility | Caterpillar CS-533 smooth | 9,960 | MDP | GC | 31.7 | 36.9 | 8 | 1.7 | 31.9 | 8 |
| 22 | White et al. (2011) | SR-25, West Lafayette, Indiana | Caterpillar CS563E smooth | N/A | MDP40 | SP-SM | 9.1 | 4.1 | 3.3 - 5.0 | 0.9 | 30 | 2.5 |
| 23 | White et al. (2011) | SR-25, West Lafayette, Indiana | Caterpillar CS563E smooth | N/A | MDP40 |  | 9.1 | 4.1 | 3.3 - 5.0 | 1.8 | 30 | 2.5 |
| 24 | White et al. (2011) | SR-25, West Lafayette, Indiana | Caterpillar CS563E smooth | N/A | MDP40 |  | 9.1 | 4.1 | 3.3 - 5.0 | 0.9 | 30 | 3.2 - 3.8 |
| 25 | White et al. (2010) | US219, Springville, NY | Caterpillar CS683 | N/A | CMV | SM | 6.0 | 24 |  | 0.9 | 30 | 4 |

First table

|  |  | Humboldt Nuclear gauge | Transtech soil density guage |
|---|---|---|---|
| Case | CMV | Dry unit weight (kN/m$^3$) | Dry unit weight (kN/m$^3$) |
| 2 | 2.578125 | 17.14397632 |  |
| 2 | 7.1875 | 18.11730175 |  |
| 2 | 7.109375 | 18.35409775 |  |
| 2 | 7.03125 | 18.95301075 |  |
| 2 | 10.46875 | 15.85989184 |  |
| 2 | 19.53125 | 17.23556646 |  |
| 2 | 25.859375 | 17.44227672 |  |
| 2 | 34.84375 | 16.19959414 |  |
| 2 | 39.296875 | 18.20361464 |  |
| 5 | 66.25641026 | 17.42019544 |  |
| 5 | 66.35897436 | 18.247557 |  |
| 5 | 58.35897436 | 17.71335505 |  |
| 5 | 55.07692308 | 17.9218241 |  |
| 5 | 53.43589744 | 18.27361564 |  |
| 5 | 50.05128205 | 18.46905537 |  |
| 5 | 46.15384615 | 18.26058632 |  |
| 5 | 44.92307692 | 18.4495114 |  |
| 5 | 47.48717949 | 18.80781759 |  |
| 5 | 49.23076923 | 18.88599349 |  |
| 5 | 49.84615385 | 19.15309446 |  |
| 5 | 54.15384615 | 18.74918567 |  |
| 6 | 26.18164738 | 16.88876875 |  |
| 6 | 59.42774341 | 17.78957879 |  |
| 6 | 44.87202439 | 17.72085246 |  |
| 6 | 46.58294486 | 17.94511702 |  |
| 6 | 38.28624351 | 18.07334669 |  |
| 6 | 41.19494124 | 18.05627145 |  |
| 6 | 43.78777673 | 18.059332 |  |
| 6 | 46.6023539 | 18.18967096 |  |
| 6 | 48.29785348 | 18.21963238 |  |
| 6 | 51.10817661 | 18.29637048 |  |
| 6 | 41.05535566 | 18.29749307 |  |

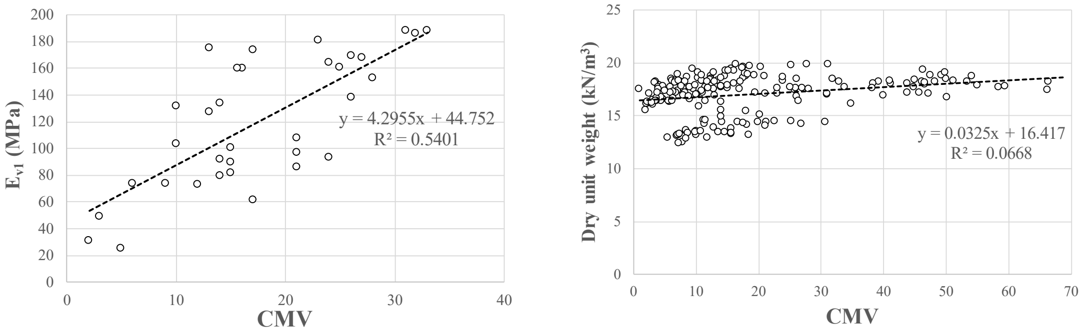
N$^{th}$ table (N >1)

Fig. 2 An example of constructing a meta-database using a relational database construction method.

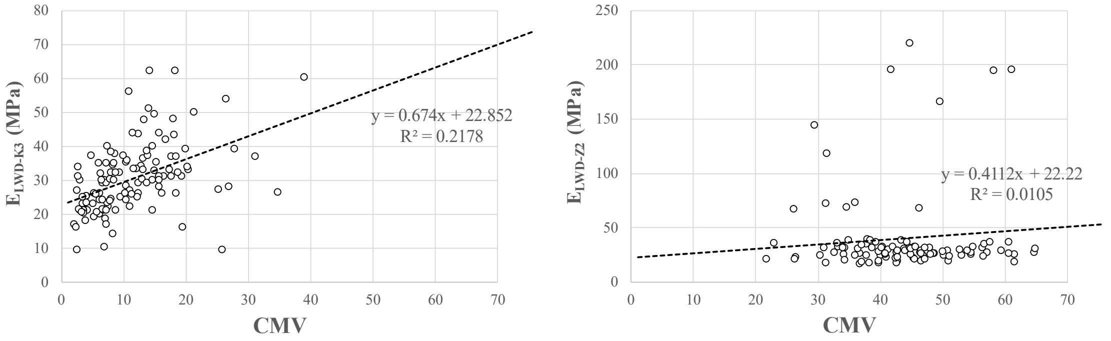
## 3. CORRELATION BETWEEN CMV AND FTV

As previously mentioned, the successful implementation of intelligent compaction in earthwork construction practice requires knowledge of ICMV and their relationships with FTV. In this chapter, we analyzed the correlation between CMV and FTV using a dataset consisting of 1,206 data pairs collected from 17 field locations (see Table 2).

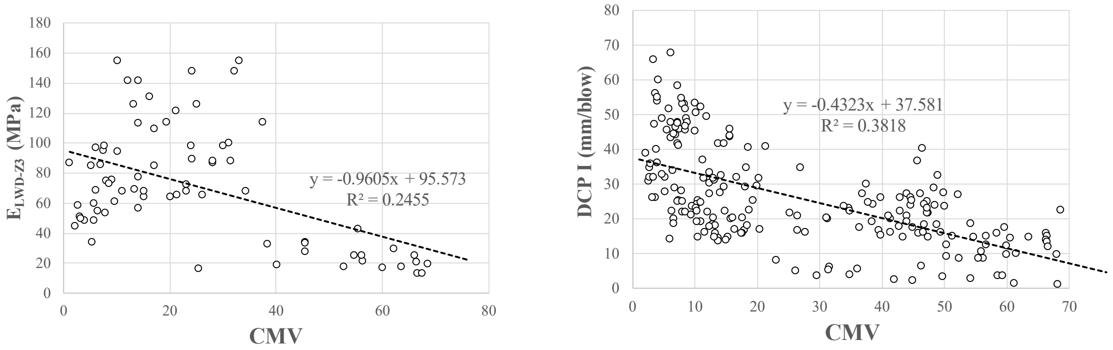
Fig. 3 presents the CMV-FTV data pairs obtained under identical conditions. To investigate the correlation between CMV and FTV, we employed a simple linear regression model with CMV as the independent variable and FTV as the dependent variable. We utilized widely-used performance indicators of linear regression models, namely the coefficient of determination ($R^2$). The coefficient of determination signifies the proportion of the dependent variable's variance explained by the independent variable in the least squares linear regression analysis. It provides a numerical measure of how effectively the model can account for the target variable. A higher coefficient of determination suggests a greater likelihood of a relationship between the independent and dependent variables.



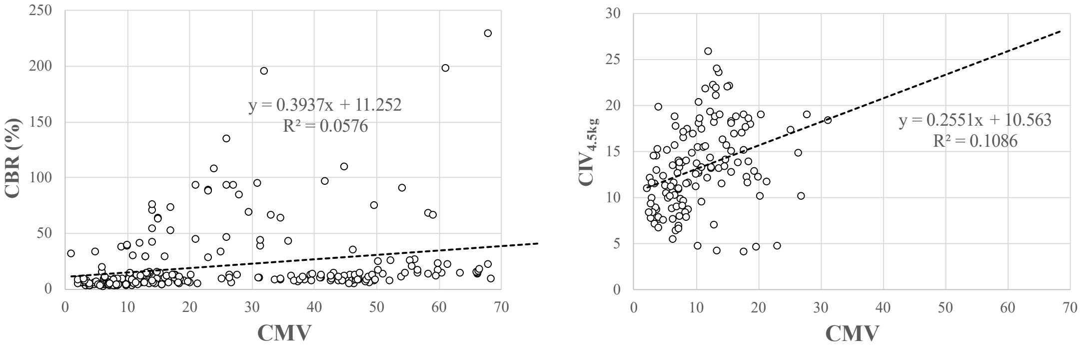
(a) CMV-PLT ($E_v$) (b) CMV-NG ($\gamma_d$)



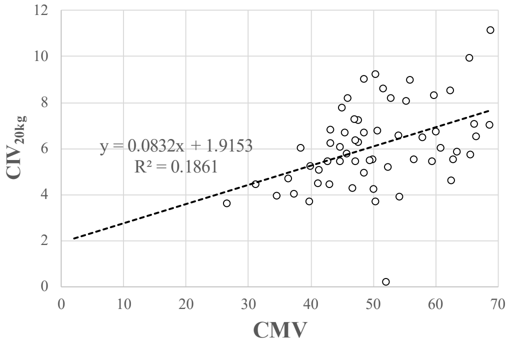
(c) CMV-LWDT ($E_{LWD-K3}$)  (d) CMV-LWDT ($E_{LWD-Z2}$)



(e) CMV-LWDT ($E_{LWD-Z3}$)  (f) CMV-DCPT (DCPI)



(g) CMV-DCPT (CBR)  (h) CMV-CIH ($CIV_{4.5kg}$)



(i) CMV-CIH ($CIV_{20kg}$)

Fig. 3 CMV-FTV Data Pairs and Simple Linear Regression Model.

CMV is an indicator that reflects the level of soil compaction. As the soil compaction increases, the CMV value also increases. In Fig. 3, the FTV represents the density or stiffness of the ground, except for DCPI, which measures the penetration depth of a cone penetrometer. We would expect to observe a negative correlation between CMV and DCPI, as higher CMV and smaller DCPI values indicate greater compaction. Conversely, we would anticipate a positive correlation between CMV and the remaining FTV, as higher CMV values correspond to higher ground density or stiffness. Overall, with the exception of $E_{LWD-Z3}$ in Fig. 3(e), the observed correlation between CMV and FTV aligns with our expectations.

Fig. 4 is a modification of Fig. 3(e), where CMV- $E_{LWD-Z3}$ data points are differentiated based on the fill material. From Fig. 4, it can be observed that the deviation of $E_{LWD-Z3}$ is attributed to the field where coarse gravel was used as the fill material. In cases where coarse gravel is used as the fill material, CMV tends to be measured significantly higher regardless of the compaction quality. This suggests that special attention is needed when applying CMV for quality control in construction sites where coarse gravel fill material is predominantly used.

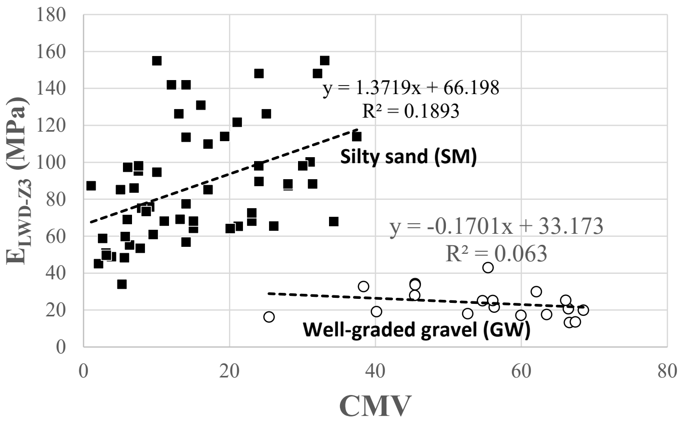


Fig. 4 Correlation between CMV and $E_{LWD-Z3}$ according to fill material types.

Except for sites where coarse gravel was used as the fill material, the observed correlation between CMV and FTV aligns with our expectations from a physical standpoint. This suggests that CMV can serve as an indicator for compaction quality control, as it exhibits a significant correlation with direct measurements of ground density or stiffness (FTV). However, the simple linear regression model presented in this study yielded a low coefficient of determination ($R^2$), indicating its limited performance. This can be attributed to the inclusion of results from various field environments without separate classification. While excluding sites showing distinct trends may improve the regression analysis results, for the purpose of this study, data points were not removed solely based on their deviation from the overall trend.

Additionally, the data collected in this study comprised CMV-FTV data pairs measured at the same specific locations, representing an "individual point analysis". However, a significant challenge arises from the fact that both CMV and FTV exhibit a coefficient of variation exceeding 30% (White et al., 2007). Given the inherent variability of CMV and FTV, deriving a linear regression model with a high coefficient of determination through individual point analysis appears challenging. Therefore, it is more appropriate to employ an “average point analysis”, where a specific-sized area is designated as a compaction management unit, and the mean values of CMV and FTV measured within that unit are used for regression analysis. Determining the appropriate size of the "specific-sized area" should be based on additional data collection and analysis. Conducting further literature reviews and field tests, along with acquiring additional data for analysis, is expected to lead to more meaningful conclusions in the future.

## 4. CONCLUSIONS

This study serves as a fundamental step towards utilizing intelligent compaction technology for earthwork quality control. It involved gathering 12 research outcomes (papers and reports) related to field studies on intelligent compaction. From these sources, a metadata database was constructed, and the correlation between CMV-FTV was investigated.

By utilizing the CMV-FTV pairs obtained from a total of 17 field locations, the correlation between them was examined. With the exception of certain sites where coarse gravel was used as the fill material, a valid correlation between CMV-FTV was observed from a physical perspective. This suggests that CMV exhibits a significant correlation with direct measurements of ground stiffness (or density), indicating its potential as an indicator for compaction quality control.

However, the simple linear regression model yielded a very low coefficient of determination, which is a performance indicator. This is likely due to the variability introduced by the type of fill material and the fluctuations observed in CMV-FTV. Specifically, considering the inherent variability of CMV and FTV, deriving a linear regression model with a high coefficient of determination through individual point analysis appears challenging. Therefore, it is more appropriate to employ an average point analysis approach, where a specific-sized area is designated as a compaction management unit, and the mean values of CMV and FTV measured within that unit are used for regression analysis. Determining the appropriate size of the "specific-sized area" should be based on additional data collection and analysis.

Conducting further literature reviews and field tests, along with acquiring additional data, and analyzing them in conjunction with the data collected in this study, is expected to lead to more meaningful conclusions in the future.

## ACKNOWLEDGEMENT

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