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Assessing the reliability of the lightweight deflectometer test for compaction control in highway subbase layers through SPSS analysis

Mehmet Tevfik Seferoğlu*[a], Ayşegül Güneş Seferoğlu[a], Muhammet Vefa Akpınar[b] Divine Iribagiza[a]

[a]Gümüşhane University, Department of Civil Engineering, Engineering and Natural Sciences Faculty, 29100, Gümüshane/Türkiye
[b]Karadeniz Technical University, Department of Civil Engineering, Engineering Faculty, 61080, Trabzon/Türkiye

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ABSTRACT

The condition of the highway base/subbase layers is critical for the durability and performance of the road pavement. Compaction control plays an important role in determining the ability of these layers to support traffic loads, their strength and stability. Various methods are used to evaluate the compaction rate of subbase layers; such as nuclear density gauge (NDG) and sand cone. These methods also have their own limitations and difficulties. While the NDG test is used to determine the compaction percentages, the lightweight deflectometer (LWD) test is used as a relatively more practical, portable and non-destructive method to measure the surface stiffness modulus (E_{mod}). In this study, the possibility of using the surface stiffness modulus obtained by the LWD test in the subbase layer instead of each other is investigated by establishing a correlation between the compaction percentages determined by the NDG test. To investigate how well the LWD results are in line with established methods, only correlation and regression analysis of SPSS software are focused on. Correlation analysis helped us assess the strength and direction of the relationships between LWD modulus values and compaction percentages, while regression analysis provided insights into the predictive capability of LWD in estimating compaction outcomes. These methods helped evaluate the reliability and accuracy of LWD as a compaction control tool, providing a deeper understanding of the role of LWD in highway subbase layer assessment.

I. INTRODUCTION

The long-term performance and structural integrity of roads depend largely on the quality of the underlying base/subbase layers. These layers must be sufficiently compacted to withstand the setbacks caused by traffic and to provide the necessary support and stability. It is important to achieve optimum compaction, as inadequate compaction can lead to premature road damage, increased maintenance costs and potential safety hazards. Various methods are used to determine the compaction percentages of highway pavement layers. For example; nuclear density gauge (NDG), sand cone, etc. However, these methods are time consuming, costly and in some cases can cause delays in the construction process.

Recently, lightweight deflectometer (LWD) testing has emerged as an extremely easy-to-apply and non-destructive tool for in-situ evaluation of the stiffness of granular soils. In addition, LWD is a more portable, faster and real-time alternative to measuring soil flexibility compared to traditional methods. Despite the many benefits provided by this method, it is known that the measurements obtained can be affected by the physical condition of the surface and the measurement depth is limited. In this respect, the LWD test is more suitable for soils that are well compacted and whose surface is smooth enough. The surface irregularities and heterogeneity of the tested soil can negatively affect the accuracy of LWD data.

*Mehmet Tevfik Seferoğlu. Tel.: +90-530-406-2462; e-mail: mtseferoglu@gumushane.edu.tr

LWD is used to determine the stiffness modulus (E_{mod}, E_{LWD}) to provide design and performance characteristics of highways, and it can also predict the behavior of the road structure under load by integrating the measurement data into mechanical-empirical formulas. The LWD testing is a very powerful method for determining the E_{mod} in the evaluation of compacted pavement layer performance [1].

NDG is a non-destructive testing method used to determine the soil compaction percentage by obtaining soil density (maximum dry unit weight) and water content. NDG testing should not be used if the content of large size (>37.5 mm) material in the mixture is more than 20% by mass [2]. NDG test is applied on soil, aggregate, asphalt and concrete layers with a depth of up to 30 cm [3]. This test method is not applicable to clean gravel or clean crushed rock due to excessive surface voids which have the potential to affect gauge measurements [4]. Although it provides highly accurate results, difficulties in practice may arise due to the requirements for the use of radioactive materials and the need for trained operators and licenses. These issues make LWD an suitable alternative in road construction works where time and accuracy are critical.

The relationship between LWD and NDG test results has been investigated by some researchers. The LWD and NDG results are closely related in obtaining the compaction percentages of granular soils [5]. The LWD provides sufficiently accurate results for quality control, even if there are minor differences between the stiffness modulus obtained from LWD and other traditional methods [6]. The data obtained from LWD and also standard density tests and concluded that LWD can be used instead of NDG testing, especially in many large-scale road construction projects, due to its simpler and faster operation [7]. The LWD is a useful method for assessing the compaction quality of unbound soils, but the accurate measurement depth is usually shallower than NDG [8].

The soil E_{mod} determined by LWD may differ due to various reasons such as layer thickness, soil type, granulometry, water content and location. Also explored the correlation between FWD and LWD results, obtaining an R^2 value between 0.5 and 0.9 [9]. In a study conducted by Singh et al. (2010), the relationships between dry unit weight and LWD deflection are investigated. It is observed that as the dry density increased, the dynamic modulus of the soil also increased. However, they did not report the correlation coefficient between the values [10]. Rahman et al. (2008) reported that there is no correlation among the California bearing ratio (CBR), falling weight deflectometer (FWD), LWD and dynamic cone penetrometer (DCP) testing devices used on Kansas highway pavements. They discussed the concept of influence depth related to the LWD, stating that this instrument is effective at depths ranging from 24 to 28 cm [11]. Livneh and Goldberg (2001) noted that the results obtained from the FWD instrument are 2.5 to 3.3 times higher than those obtained from the LWD device for the same area [12]. Steinert et al. (2005) determined a correlation coefficient between the compaction percentages of the subgrade and the results obtained from the LWD, revealing an R^2 value ranging from 0.1 to 0.5. This suggests that the relationship is quite weak [13].

As a result, the increasing body of literature supports the adoption of the LWD as a reliable tool for compaction control in highway construction. While NDG and other traditional destructive tests continue to be important, the rapidity, portability, and non-destructive nature of LWD make it a good alternative. Further research into the correlation between LWD and NDG results will play a significant role in shaping standards for LWD compaction control, potentially leading to wider acceptance of LWD in road construction projects.

In this study, SPSS analysis is used to examine the relationship between LWD measurements and a traditional compaction control method (NDG). Among the various analytical tools available in SPSS, only correlation analysis and regression analysis are focused on to explore how well LWD results align with the established methods. Correlation analysis helped us assess the strength and direction of the relationships between LWD modulus values and compaction percentages, while regression analysis provided insights into the predictive capability of LWD in estimating compaction outcomes. These methods helped in evaluating the reliability and accuracy of LWD as a compaction control tool, offering a deeper understanding of LWD role in highway subbase layer assessment.

II. EXPERIMENTAL METHOD

A 25 cm-thick plant-mix subbase (PMSB) type-B layer, which is laid on a 5 m wide strip of a highway with a 10 m platform width on a section between 65^{200}-96^{000} km of the Trabzon-Kürtün (Gümüşhane) highway, is selected as the study area. Aggregates of three different grain size groups, (19-50 mm), (7-19 mm) and (0-7 mm) produced in the quarry, are used for the subbase layer.

The LWD and NDG tests are carried out respectively on fifteen different measuring points on the study area, with 2.5 m between them (Fig. 1). Thus, a comprehensive data set is obtained in order to compare the results of both methods. The stiffness modulus value of the subbase layer at determined points is evaluated with the LWD test, and its density is evaluated with NDG.

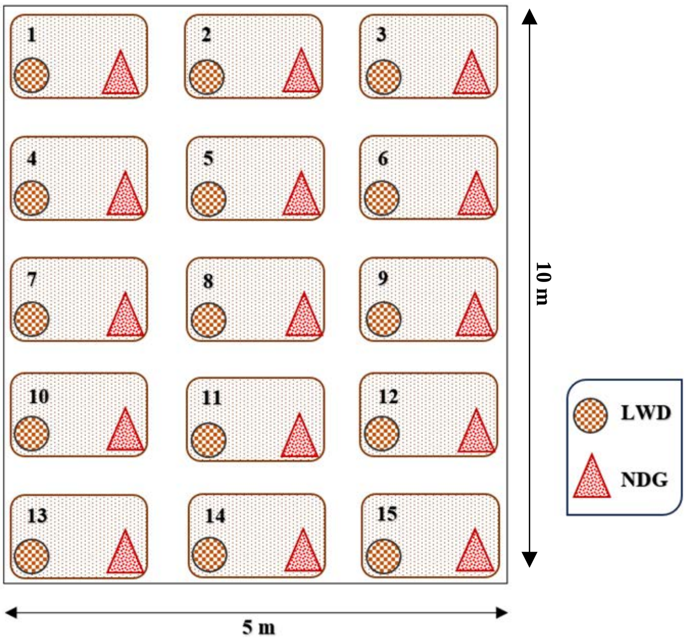

Figure 1. The LWD and NDG measurement points

2.1 Lightweight Deflectometer (LWD) Test

LWD is a portable test method used to evaluate the stiffness of soil and unbound pavement layers in road construction. It works by dropping a known weight onto a loading plate placed on the surface of the material to be tested, creating a force that causes deflection on the surface. This deflection is measured by sensors, and from these measurements, the device calculates the material's stiffness modulus (E_{mod}, E_{LWD}). The E_{mod} indicates the material's stiffness, which is critical in assessing whether a compacted layer meets the required strength for construction.

In this study, LWD test is carried out according to ASTM 2583 to determine the stiffness of PMSB [14]. In test, falling mass is 10 kg, the diameter of the loading plate is 300 mm. After the LWD device is placed on the surface of the subbase layer, the depth-dependent stiffness values are automatically measured by this device for the subbase surface and for depths of 5, 10 and 15 cm.

2.2 Nuclear Density Gauge (NDG)Test

The NDG test is a non-destructive method used for controlling soil compaction in the field. NDGs take measurements using a radioactive isotope source placed either on the soil surface or within the ground. The isotope source emits photons (gamma rays) that are detected by sensors in the measurement device's lower unit. Dense soils absorb more radiation than loose soils and the readings reflect the overall density. Additionally, moisture content can be measured within a few minutes, as the gamma rays are absorbed by both water and soil. Denser soils and those with higher water content absorb more gamma rays. The NDG testing can be applied at depths ranging from 5 to 37.5 cm. In this study NDG test is carried out according to ASTM D 6938-23 [4].

2.3 Device Positioning

Measurements are conducted on a single 5 m wide lane of the road, which has an approximate platform width of 10 m. A total of fifteen measurement points is created with a distance of 2.5 m between them in both directions. (Fig. 2). At these marked fifteen measuring points, first the LWD test is performed and then measurements are taken with NDG.

Figure 2. Study area **(a)** Measuring points **(b)** Positioning of measuring instruments

2.4 Statistical Analysis

Data obtained from the LWD and NDG experimental tests conducted on the study area are subjected to a statistical analysis using SPSS software. The analysis focused on determining the correlations, regression patterns and variances between the results obtained from the tests and provided a detailed comparison of their effectiveness in measuring compaction on a well-compacted road subbase section. Thus, the relationships between the methods are determined and an evaluation is made whether these tests could be used interchangeably in the field.

III. RESULTS AND DISCUSSIONS

3.1 Results Related to Subbase Layer

A set of test results related to the relevant subbase layer aggregates and the criteria of the Türkiye Department of Transportation (TürkiyeDOT) Technical Specifications [15] are shown in Table 1

Table 1. Aggregate test results and specification criteria

Tests	Test results	Specifications
Resistance to Weather Effects *(%)*	2.4	< 20
Abrasion Loss *(%)*	22.0	< 50
Flatness Index *(%)*	13.0	< 40
Liquid Limit	N.P.	< 25
Plasticity Index	N.P.	< 6

The data obtained from the sieve analysis tests performed on the aggregates are determined as design granulometry. The design gradation values remained within the limits specified in the TürkiyeDOT Technical Specification for plant-mix subbase (PMSB) type-B. The maximum aggregate grain size is 50 mm as specified in the TürkiyeDOT Technical Specification for PMSB type-B [15]. The design granulometry of PMSB type-B and the lower and upper limits of the specification are shown in Fig. 3.

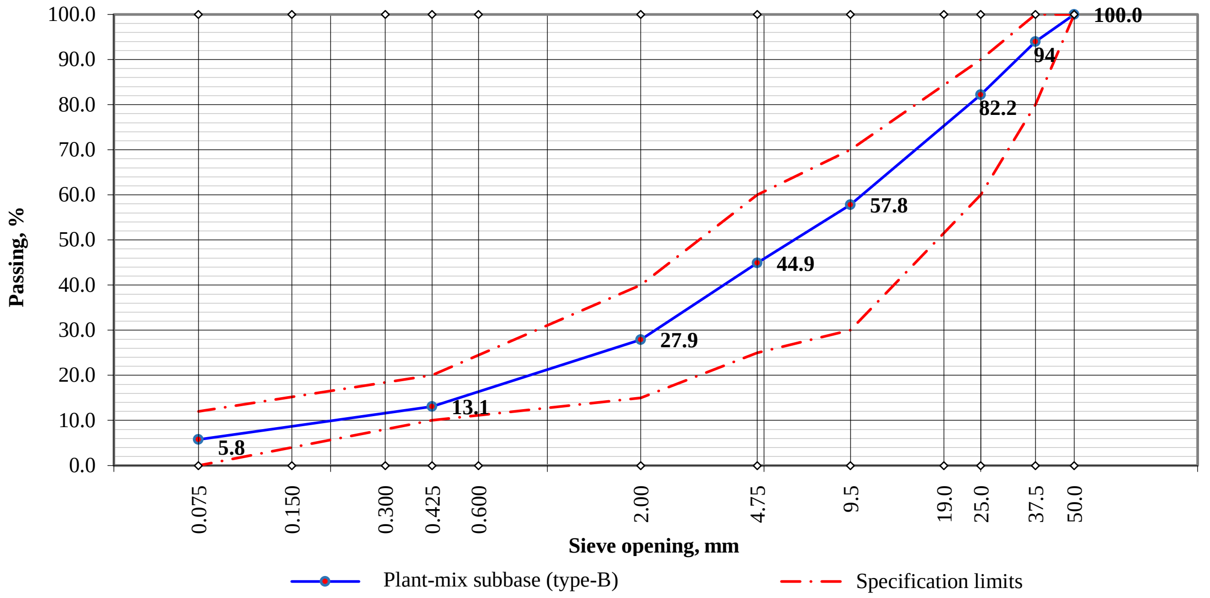

Figure 3. PMSB type-B mixture grain size distribution curve and specification limits

The relationships between the maximum dry unit weight and optimum water content of the PMSB layer are determined using the modified proctor method. Additionally, the soaked CBR values of the samples compacted with modified proctor energy are also determined, and the results are presented in Table 2.

Table 2. Modified proctor and soaked CBR test results

Modified Proctor Test	Maximum dry unit weight *(ton/m³)*	2.254
	Optimum water content *(%)*	4.35
Soaked CBR Test	CBR *(%)*	120

The minimum soaked CBR value criterion of 50% for PMSB type-B, as specified in the specification [15], is comfortably exceeded at 120%. PMSB type-B is compacted to at least 98% of the maximum dry unit weight, based on the aggregate design gradation within the specified tolerance limits.

3.2 Results Related to LWD and NDG

The road section in the study area is well compacted, with nuclear test results indicating an average compaction level of 99%. Across the test points, minimal variation is observed in compaction, with values ranging from 98% to 100%. The average water content from the NDG tests is 5%, signifying uniformity in moisture distribution. When analyzing the regression and correlation values between the E_{LWD} and NDG compaction percentage at different depths, it’s important to focus on the strength and direction of the relationships.

The E_{mod} values obtained from LWD and NDG tests are shown in Fig. 4. The correlation coefficient obtained by the SPSS analysis from the distribution graph in Fig. 4 is determined as -0.465.

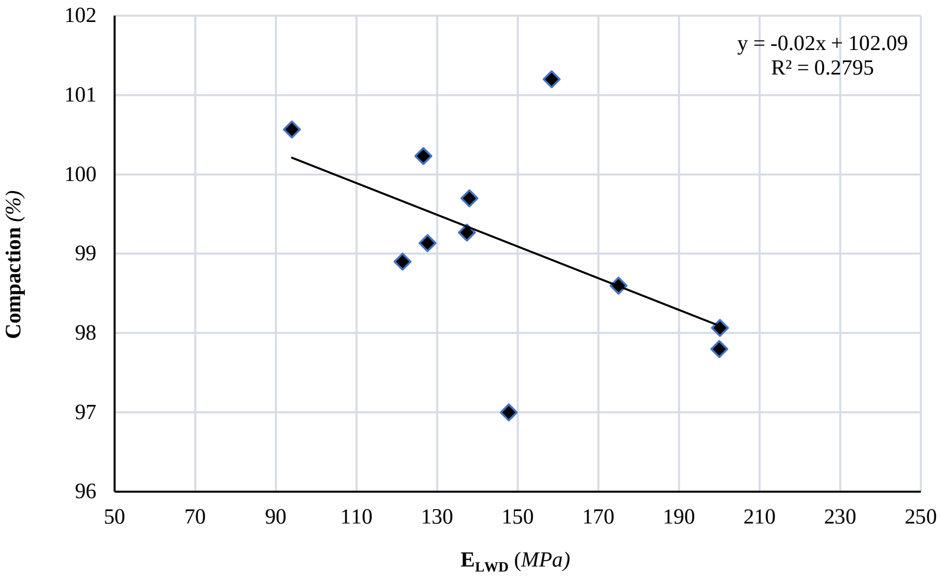

Figure 4. The regression analysis between LWD and NDG results at the surface level

Fig. 5 provides a comparison of the E_{mod} values obtained from the LWD and the compaction percentages recorded by the NDG at a depth of 5 cm below the surface. The distribution graph generated from the SPSS analysis, illustrated in Fig. 5, reveals a correlation coefficient of 0.245836.

Fig. 6 offers a comprehensive comparison of the E_{mod} values obtained from the LWD and the compaction percentages measured by the NDG at a depth of 10 cm beneath the surface. The distribution graph produced from the SPSS analysis, depicted in Fig. 6, demonstrates a correlation coefficient of -0.05688.

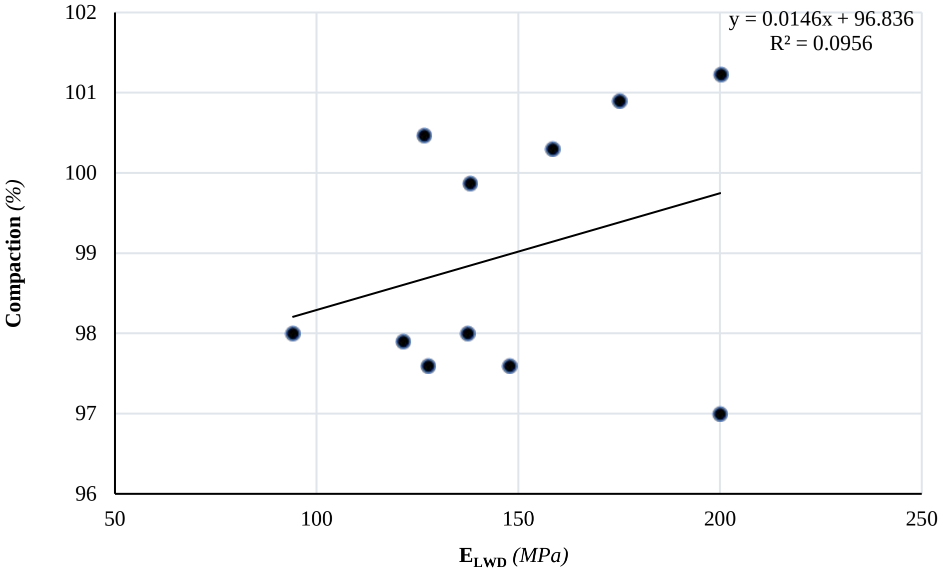

Figure 5. The regression analysis between LWD and NDG results at a depth of 5 cm

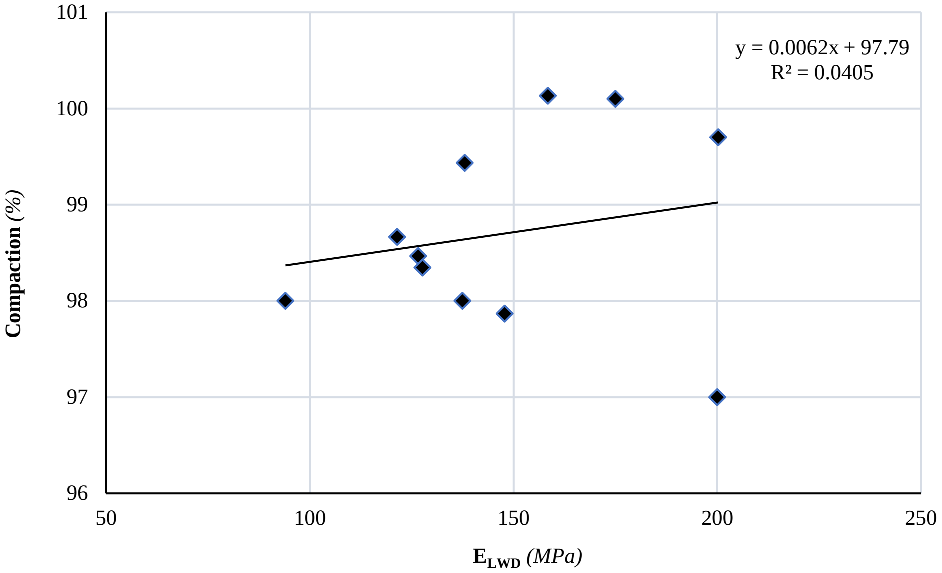

Figure 6. The regression analysis between LWD and NDG results at a depth of 10 cm

Fig. 7 presents a comparison of the E_{mod} values derived from the LWD and the compaction percentages obtained from the NDG at a depth of 15 cm below the surface. The distribution graph generated from the SPSS analysis, illustrated in Fig. 7, reveals a correlation coefficient of 0.196679.

As seen above from Fig. 4, starting from the surface, ground level, the negative correlation (-0.465) suggests that as the E_{LWD} increases, the compaction percentage measured by NDG tends to decrease slightly at the surface. The regression value also indicates a weak relationship between the two variables. This might imply some discrepancy or inconsistency between the two methods at this shallow level, possibly due to surface irregularities or environmental factors affecting the LWD readings.

The positive correlation (0.245836) in Fig. 5 suggests a weak but direct relationship between the E_{LWD} and NDG compaction, meaning as one increase, so does the other. The low regression coefficient indicates the relationship is not strong, but it is positive compared to the surface level.

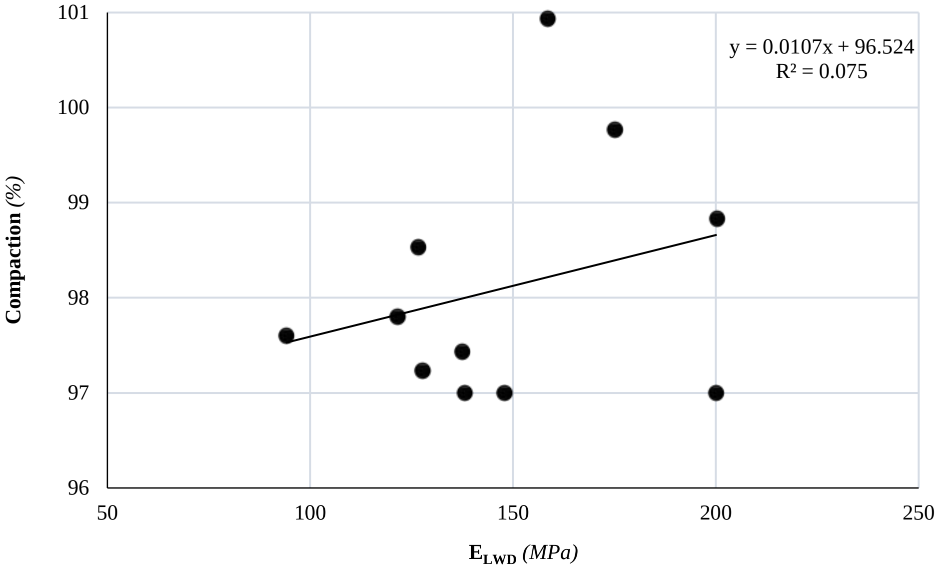

Figure 7. The regression analysis between LWD and NDG results at a depth of 15 cm

For Fig. 6 at 10 cm of depth both the regression and correlation values are very close to zero (-0.05688), indicating almost no relationship between the E_{LWD} and NDG compaction at this depth. This could suggest that at this depth, the two methods are measuring different characteristics, or the accuracy of one or both methods decreases with increasing depths.

Although the correlation remains weak at 15 cm of depth, it is positive, suggesting a minor direct relationship between E_{LWD} and NDG compaction at this depth. The low regression value still implies that the LWD and NDG do not strongly align at deeper levels, though the relationship improves slightly compared to the 10 cm depth.

From the surface, 5 cm, 10 cm and 15 cm of depth, the results indicate that the correlation between LWD and NDG varies with depth, being weakest at 10 cm and slightly improving at 15 cm. The discrepancies at the surface may be due to factors such as surface roughness or external influences affecting LWD readings, while the deeper measurements show weak to moderate positive relationships. This suggest that LWD results can may not always correlate perfectly with NDG results, especially at near-surface depths.

Considering that the correlation coefficient between LWD and compression range in the study of Steinert et al. (2005) [13] is between 0.1-0.5, which they describe as a weak relationship, it can be said that a low relationship has been established between NDG and LWD for all depths obtained from the study. More realistic results can be obtained in cases such as more precise control of the interface conditions on the contact surface of the LWD/NDG devices with the subbase layer. Since the LWD device takes measurements from a point location, the fact that the tip of the measuring tool comes to a different point such as a different aggregate, soil, or porous structure at each measurement point may also be the reason for the low correlation. It is thought that performing the tests under laboratory conditions on a completely homogeneous layer will increase the correlation between NDG and LWD.

IV. CONCLUSIONS

In this study LWD and NDG measurements are taken at fifteen different locations on a road section between Trabzon and Kürtün (Gümüşhane); on the surface, at depths of 5 cm, 10 cm and 15 cm from the surface. Regression and correlation analyses are performed in the SPSS program to examine the convergence of LWD and NDG tests on the results. As a result of the evaluation, it is seen that the measurement depth played a major role in the correlation between LWD and NDG.

The LWD measurements show weaker correlation and inconsistent regression trends with increasing depth compared to surface readings of NDG measurements. The decreasing regression coefficients and correlations with increasing depth (as low as 0.0032 for regression and -0.05688 for correlation at 10 cm) are consistent with previous studies [5] emphasizing the depth of surface influence.

The observed discrepancy between LWD and traditional methods such as NDG highlights the need for further calibration of LWD measurements, especially when applied to multilayered or complex superstructures. In addition, the weak statistical significance, as indicated by the p-values in both correlation and regression analyses, requires more comprehensive datasets to establish stronger relationships.

From a statistical point of view, according to SPSS analysis, although LWD provides useful information on surface hardness, its role in determining compaction quality at different depths remains unclear, which may affect its general usability in highway construction quality assurance programs.

Despite the statistical limitations, LWD remains a highly practical tool for field use. Its advantages, such as the elimination of radioactive materials and ease of transportation, cannot be ignored. However, the weak correlations observed in this study imply that LWD may need to be supplemented by other methods (e.g., Sand Cone or NDG) to ensure accurate compaction control, particularly in critical or high-load-bearing sections of road construction. Additionally, its utility may be more relevant for surface layer analysis, where it has demonstrated higher reliability.

Based on this research, in conclusion, even though LWD could still be useful as a complementary tool for surface-level assessments, especially given its speed and non-destructive nature, the statistical analysis shows that LWD offers limited accuracy in replicating the results of NDG tests, particularly at greater depths. While LWD’s ease of use and quick results make it a valuable tool in road construction, it cannot fully replace traditional methods in terms of depth-sensitive compaction control without further refinement and calibration. Thus, a hybrid approach, utilizing both LWD and traditional methods, may currently offer the best balance between practicality and accuracy in field compaction assessments.

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