Innovative Infrastructure Solutions (2023) 8:101
https://doi.org/10.1007/s41062-023-01061-5

REVIEW

A comprehensive review on non-destructive testing using LWD and Geogauge for quick QC/QA of pavement layers

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Received: 18 November 2022 / Accepted: 30 January 2023 / Published online: 16 February 2023

Abstract

Roads are extremely important to a country's socioeconomic growth. Pavement performance depends on its ability to carry commercial traffic over its design life. During the construction and before opening pavement layers to traffic, they must pass Quality Control (QC) and Quality Assurance (QA) processes. Engineers use unit weight-based QC/QA methods like core cutter, sand replacement, etc. Light Weight Deflectometer (LWD) and Geogauge are replacing them. These devices are light, portable, and provide data quickly. These technologies provide the elastic/deformation modulus of compacted pavement layers to replace the unit weight-based method. The paper describes the work that has been accomplished so far and the latest developments on Geogauge and LWD. This paper aims to provide insights on these technologies' definitions, testing methods, significance, limitations, working principle, modulus improvement for stabilized materials, repeatability, and use in QC/QA of pavement layers constructed using various geomaterials, including correlations between modulus and other physical parameters, and control charts for QA/QC. It also includes modulus ranges for conventional road materials. This paper especially discusses the ability of these devices to measure the improvement in stiffness/modulus due to soil reinforcement or stabilization. The process of QC/QA involves exploring the range of target deformation modulus values for both devices related to conventional relative compaction for a specific geomaterial of the site for QC/QA purposes; researchers advise building a test pad before actually starting to build roads. Many studies are based on Target values (TVs) which do not provide UCL (upper control limit) which could lead to over-compaction. This review discusses control charts that provide both LCL (lower control limit) and UCL. This work has been performed as the presently used unit weight method is time-consuming, laborious, and destructive; thus, there is a need to shift from a unit weight-based method to a modulus-based method which is time efficient, non-laborious, and non-destructive for the QC/QA process. This paper provides a comprehensive review of two modulus-based devices, namely, LWD and Geogauge. It can be stated that these tools efficiently assess the pavement layers' quality during construction and allow for prompt mitigation. These devices also have the ability to record and determine the increase in stiffness/modulus over time due to the curing of non-conventional materials. This is one way to complete road projects on time and benefit society.

Keywords NDT · LWD · Geogauge · Quality control · Quality assurance · Target values · Control charts

Introduction

The road system of a country determines how well it can do economically, industrially, socially, and culturally. Modern highways require vehicles to operate safely and efficiently at high design speeds. Pavements must be built with QC and QA in mind if they are to last for a long time, need little maintenance, and cost as little as possible.

The compaction of pavement layers is an important factor in the construction of roads or highways. Getting proper compaction is essential for a highway's durability and stability. So, to improve the engineering characteristics of highways, it is important to control compaction while they are being built. The goal of compacting the road layers is to also improve their mechanical properties in addition to their dry unit weight [1]. At the moment, the quality of highway construction is judged by comparing the maximum dry unit

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weight found during standard or modified Proctor testing in the laboratory with the field unit weight measurements. A field dry unit weight can be measured destructively using the core cutter, rubber balloon, or sand cone methods, or non-destructively using a nuclear density gauge (NDG). The sand cone test is often used to measure the in situ density of compacted layers to figure out how well a pavement is compacted. Tests such as these are time-consuming, tedious, and sometimes not viable to perform to specifications, as well as posing a health risk because nuclear density gauges are hazardous [2]. According to experts, the present unit weight-based quality control methods are labour-intensive, slow, dangerous, uncertainly accurate, and unsuitable for situations where site materials vary along tested sections [3, 4]. According to Lenke et al. [5], these quality control methods are commonly adopted because of their simplicity and relatively low cost. As Pinard [6] pointed out, the unit weight criteria used do not reflect the engineering characteristics of soils under highway conditions. Similarly, Fleming [7] came to the same conclusion. Also, the stiffness modulus of the base and subbase layers is thought to be an indicator of how well they support the concrete or asphalt layers on top [8].

In the mechanistic-empirical design of asphalt pavements, the resilient modulus is used to express the strength of the layers. It is critical to execute enough compaction during construction to ensure that the compacted layer modulus meets the design resilient modulus. This will aid in the prevention of early-life pavement problems such as rutting, fatigue, and potholes. The dry density and moisture content of the subgrade are often the only things checked during traditional QC procedures during subgrade construction. Although the resilient modulus depends on moisture content and dry density, it also depends on the kind of material, the kind and quantity of additives (stabilizers), and the material's stress condition. As a result, dry density and moisture content are insufficient to determine the resilient modulus of the pavement layers during construction, and they are also insufficient indicators of compaction level.

The QC/QA processes employed during construction should thus strongly match the performance parameters employed during design. Materials' elastic modulus, also known as stiffness modulus or deformation modulus, is a critical performance criterion for built-up highway layers. It has been stated that a variety of non-destructive test tools, like the Light Weight Deflectometer (LWD) and Geogauge, can evaluate the in situ elastic stiffness modulus of highway materials. In addition to being simple to use, portable, and well-designed, these tools also quickly determine the modulus of pavement layers [9]. Several studies on these modulus-based technologies have focused on the QA/QC of non-reinforced pavement layers. Few studies have been done using these devices on pavement layers that have been reinforced or stabilized, though.

It is generally believed that LWD and Geogauge are fancy devices. These devices, however, are commonly used in research and practice for estimating the stiffness or modulus of pavement layers and for quality control during pavement layer construction. As these devices are better than destructive testing in many ways, users can quickly judge quality, make changes during construction without delay, and finish the project on time. This paper's novelty is its addition to previous work by the accumulation and demonstration of each and every result, as well as the latest work in this area that could be relevant to modulus-based QC/QA of pavement layers using LWD and Geogauge devices. There is also a discussion of the little research that has been done on the performance of these NDT devices on treated or stabilized pavement layers. Although many researchers have established QC/QA target values, control charts are rarely used. According to the literature, more research is required to develop specifications for QC/QA assessment using LWD and Geogauge. There is also a lack of a proper and up-to-date review of the developments in the use of Geogauge. So, the goal of this study is to give a full review of the work that has been done on non-destructive testing for measuring deflection, stiffness using LWD, and elastic modulus using Geogauge. Work has been done on various pavement layers, a wide variety of data, and how to interpret it for quality control and quality assurance. The objective of this comprehensive review is to find potential areas where little work has been done or is untouched yet.

Modulus and stiffness

Modulus and stiffness are two separate mechanical characteristics. A material with no physical boundaries has a property called modulus. The modulus of a material that is 0.1 m thick, and one metre thick is equal. Fundamental to the engineering properties of all materials is the Young's modulus, a measurement of the stress to strain ratio. It is sometimes referred to as the elastic modulus, modulus of elasticity, coefficient of elasticity, or deformation modulus. Stiffness is a property of a structure that measures its resistance to deflection. The physical dimensions of a material, its modulus, and boundary circumstances, such as how it is supported, held or confined, can all have an impact on stiffness. If a structure's thickness changes, its stiffness will change as well. In order to minimize the deflection of each component and prevent permanent damage, stiffness is the parameter of choice [10].

The elastic modulus and stiffness of prepared soil and aggregate can be measured in-place using the hand-portable Humboldt GeoGauge® [11]. After the construction of the test specimen, the LWD is used to calculate the stiffness of the pavement layers in terms of their elastic modulus

[12]. The purpose of Dynatest LWD is to measure "surface modulus" (also known as stiffness), which is the underlying structure's response to a transient deflection caused by dynamic stress delivered through a circular bearing plate [13]. Researchers have used the elastic modulus as a parameter for the QC or QA. Table 1 provides the nomenclature used by various researchers for elastic modulus.

Testing methods for QC/QA

Road structures should meet certain requirements to build safe, serviceable, durable, and economically feasible highways/roads. Structures must possess specific characteristics to meet these requirements. The description of design requirements, operational guidelines, technical specifications, testing and acceptance criteria, and workmanship in codes of practise and contract documents serve as vehicles for achieving this. Ultimately, the quality of highways/roads is determined by the successful and reliable application of these strategies. Everyone working on a highway or road has a fundamental desire to deliver high-quality work. The idea of "quality" has been described as the sum of all the attributes and qualities that contribute to a service or product's capacity to meet explicit or implicit demands [IRC 57] [26]. Table 2 summarises the comparison of QC and QA as defined by AASHTO [27, 28].

There are destructive and non-destructive methods of testing for QC/QA, shown in Fig. 1. Table 3 summarises their merits and demerits.

Significance of modulus/stiffness-based NDT

In addition to being simple and portable, modulus-based compaction testing devices have numerous economic and time-saving advantages. As a result of its non-labour-intensive and non-destructive nature, the process of quality assessment is highly cost-efficient. The capacity to gather a

Table 1 Nomenclature of modulus

Technical term	Author	References
Dynamic soil modulus	Stamp & Mooney, 2013	[14]
Composite modulus	Lin et al., 2006	[15]
LWD modulus	Bisht et al., 2017; Ebrahimi & Edil, 2013; kavussi et al., 2019	[16–18]
Elastic modulus	Nazzal et al., 2007; Sabouri et al., 2021; Wright et al., 2020	[12, 19, 20]
Stiffness modulus	Fleming, 2007; Volovski et al., 2018	[21, 22]
Dynamic elastic modulus	Meocci et al., 2017	[23]
Deformation modulus	Duddu and Chennarapu, 2022; Umashankar et al., 2016	[24, 25]

Table 2 Comparison between QC and QA [27, 28]

Quality control (QC)	Quality assurance (QA)
The processes involved in making a product's quality what it should be	The processes involved to make sure that a product is of appropriate quality
It is done during the construction period	It is done after construction
It involves the preparation and execution of a QC plan by the construction contractor	It involves quality checks and acceptance/rejection of the project lots by the owner
The construction contractor is accountable for it	The highway agency, the National Highway Authority of India, for example, is accountable for it

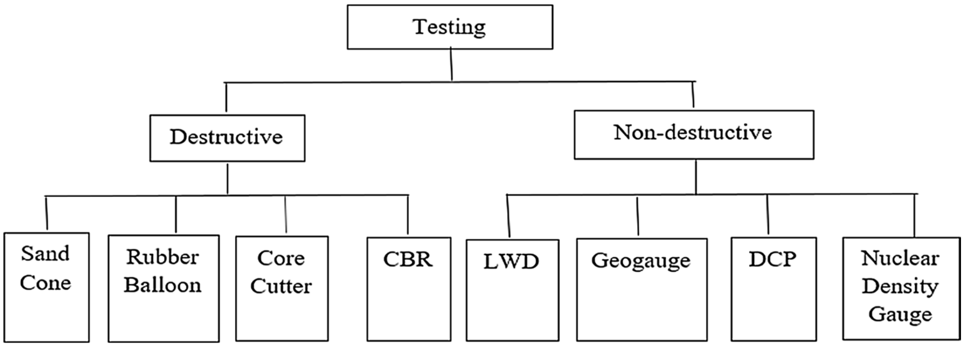


Fig. 1 Types of QC/QA testing

Table 3 Description of QA/QC tests

Function	Destructive	Non-destructive
Examples	Sand cone test, Rubber Balloon Test, Core cutter test	LWD, Geogauge, DCP
Merits	Easy to Operate Accurate and Reliable Low Cost Wide acceptance Portability	Quick and non-intrusive Easy to operate Effortless Portability Data storage
Demerits	Laborious and time-consuming Excavated material required to be recovered carefully, Discontinuous operation	Shallow Influence depth, Sensitive to seating conditions

lot of data quickly also benefits from the reduction in time [29]. In situ testing of compacted soil using these devices is quick and easy [30].

Maintaining uniformity in the paving application is critical since how well a pavement works over time and how much maintenance it requires are directly related to how stiff each layer is. Non-uniform structural stiffness is a sign of these issues, since non-uniform compaction during construction can lead to premature breakdowns. Earthworks can be easily identified as non-uniform, while voids and discontinuities can be revealed.

The stiffness/modulus-based devices have an advantage over other in situ testing devices [31]. Because of its non-destructive nature, it's sometimes necessary to take multiple measurements at the same spot over time. This is done to make sure that the laying process goes well, and if it does not, the right steps can be taken.

Limitations modulus/stiffness-based NDT

The effect radius of the Geogauge spans a ranges from 220 to 310 mm, according to earlier research based on both experimental tests and finite element analysis. The manufacturer of Geogauge, Humboldt, advises using it up to 70 MN/m for layer stiffness measurements and up to 610 MPa for in situ modulus measurements [29]. The study by Chen et al. [32] says that the Geogauge should only be used up to 23 MN/m because measurements of stiffness above this value may be less accurate. Also, the results can be inaccurate if proper seating of the equipment on the surface is not ensured. Geogauge applies a very small load that does not mimic the actual traffic load.

In contrast, LWD only provides the combined stiffness of all the layers up to an influence depth of 0.9 to 1.1 times the diameter of the plate, while a few researchers have found that, depending on the type of LWD device, the force applied, stiffness of the material, and the load plate radius, the influence depth can also be 1–1.5 times to as high as 2 times the plate diameter [21, 22, 33–36]. The LWD has a shorter depth of influence compared to the falling weight deflectometer (FWD), due to its decreased maximum applied force and load pulse time. It is thus suited for the structural evaluation of single-layer during construction [37].

Description of the stiffness/modulus-based technologies

Light weight deflectometer (LWD)

LWD is sometimes called PFWD (Portable Falling Weight Deflectometer) [38, 39]. LWD is a movable falling weight deflectometer that allows for fast readings without disturbing the earth. Table 4 lists the LWD variations: Zorn, Prima, Dynatest, TFT, etc. Each kind has many similarities in its operating principle, but differences in mode of operation and design lead to varying results [4, 14, 34, 40]. With a falling weight of 10 kg, the Dynatest 3031 LWD weighs 22 kg (Table 5). Figure 2 shows the LWD's transportation-lock pin and guiding rod with stabilizer for safe operation. It has a load range greater than 15 kN [41].

Principle

The LWD load range is over 15 kN. The loading plate has 300, 150, and 100 mm diameters. It measures force as well as deflection. The deflection produced by lowering a 10 kg load under gravity is measured by a centre geophone sensor. The falling load hits a rubber pad, producing a 15–30 ms load pulse. The Boussinesq static analysis uses observed ground deflection and applied mass to calculate stiffness. 3031 LWD's load cell measures 0–25 kN. The geophone at the loading plate's centre has a 1 m resolution and a 0–2200 m range [39]. A basic deflection bowl can be produced by models with three geophones. LWD test findings are based on a homogeneous, linear elastic, isotropic half-space under a circular load [42]. Using the Boussinesq solution and the measured centre deflection, Eq. 1 calculates the dynamic deformation modulus [31].

$$E_{LWD} = \frac{K(1-\mu^2)\sigma \times R}{\delta_c} \tag{1}$$

where E_{LWD} is the LWD dynamic modulus, K is the plate rigidity factor (2 and π/2 for flexible and rigid plates, respectively), δ_c is the centre deflection, R is the radius of the plate, σ is the applied Stress, and μ is the poisson's ratio of soil.

Table 4 Specifications of different types of LWD (Enhanced after [36])

Characteristic	CSM	Zorn	Prima	Dynatest	Loadman	TFT
Plate style	Solid	Solid	Annulus	Annulus	Solid	Annulus
Plate diameter (mm)	200, 300	150, 200, 300	100, 200, 300	100, 150, 200, 300	130, 200, 300	100, 150, 200, 300
Plate mass (kg)	6.8, 8.3	15	12	Not reported	6	Variable
Plate thickness (mm)	Not reported	45, 28, 20	20	20	Not reported	Not reported
Drop mass (kg)	10	10	10, 15, 20	10, 15, 20	10	10, 15, 20
Drop height (m)	Variable	0.72	Variable	Variable	0.8	Variable
Damper	Urethane	Steel spring	Rubber	Rubber Pad	Rubber	Rubber
Force means	Yes	No	Yes	Yes	Yes	Yes
Plate resp. sensor	Geophone	Accelerometer	Geophone	Geophone	Accelerometer	Geophone
Impulse time (ms)	15–20	18 ± 2	15–20	15–30	25–30	15–25
Max load (kN)	8.8[a]	7.07[a]	1–15[a]	15[a]	20[a]	1–15[a]
Contact stress	User defined	Uniform	User defined	User defined	Rigid	User defined
Poisson's ratio	User defined	0.5	User defined	User defined	0.5	User defined

[a] Depend on drop height and damper

Table 5 Dynatest LWD parameter specification

Parameter	Specification
Total weight	22 kg
Drop height	850 mm max
Drop Weight	10 kg
Loading plate diameters	100 mm, 150 mm, 300 mm
Loading range	> 15 KN
Pulse duration	15 > 30 ms

Factors influencing the LWD dynamic elastic modulus

Plate rigidity factor This depends on the material and plate rigidity. Flexible plates demonstrate approximately uniform contact pressure in clayey, silty, and sandy soils. Contact pressure is not uniform for a rigid plate. For sandy soils, it varies from minimum at the edges to maximum at the centre, whereas for clayey soils, it varies from maximum at the edges to minimum at the centre. Figure 3 exhibits plate rigidity and contact pressure.

Applied stress It was found that the applied stress, which depends on the size of the plate, has a considerable effect on the LWD modulus value [45]. It has been determined that the contact pressure for the loading plate with a 100 mm diameter is approximately 8–9 times higher than that for the plate with a 300 mm diameter [15]. The apparatus is made to create a peak contact stress of between 100 and 200 kPa, depending on the size of the loading plate and the force of the impact. This is similar to the stress pulse that is created on a base or subgrade layer when traffic load is applied to a finished pavement [4, 35, 40]. The correlation between applied vertical tension and modulus is significant [16, 46]. Table 6 provides the preferred range of average contact stress levels for testing from Dynatest [44].

Loading plate diameter An important factor in determining the modulus of layers is the diameter of the loading plate. Loading plate diameters used can be 100 mm, 200 mm, or 300 mm. In comparison with the 300 mm loading plate, the 100 mm loading plate had moduli that were almost 1.5 times greater. Depending on the observed modulus, the LWD's manufacturers also recommend alternative plate sizes for various pavement structures. Therefore, a plate size of 300 mm is advised when the modulus is less than 125 MPa. When the modulus is between 125 and 170 MPa, 200 mm plates are suggested, and 100 mm when over 170 MPa [15].

Poisson's ratio Poisson's ratio is an indication of soil deformability that characterizes the ratio of lateral and longitudinal deformations of the soil, which determines the elastic modulus. The soil's Poisson's ratio must be calculated via triaxial compression or lateral pressure measurement. Its value is needed to measure the material's elastic modulus [29]. After experiments, Poisson's ratio values for different materials are listed in Table 7.

Working of LWD

A 10-kg impulsive load slides down a guide tube to a rubber pad damper element after being released. The apparatus has gripping magnets that keep the weight from dropping while maintaining the appropriate height. The loading device is mounted on a cantering ball in the centre of the load plate so that it can only transmit a vertical load to the plate. There

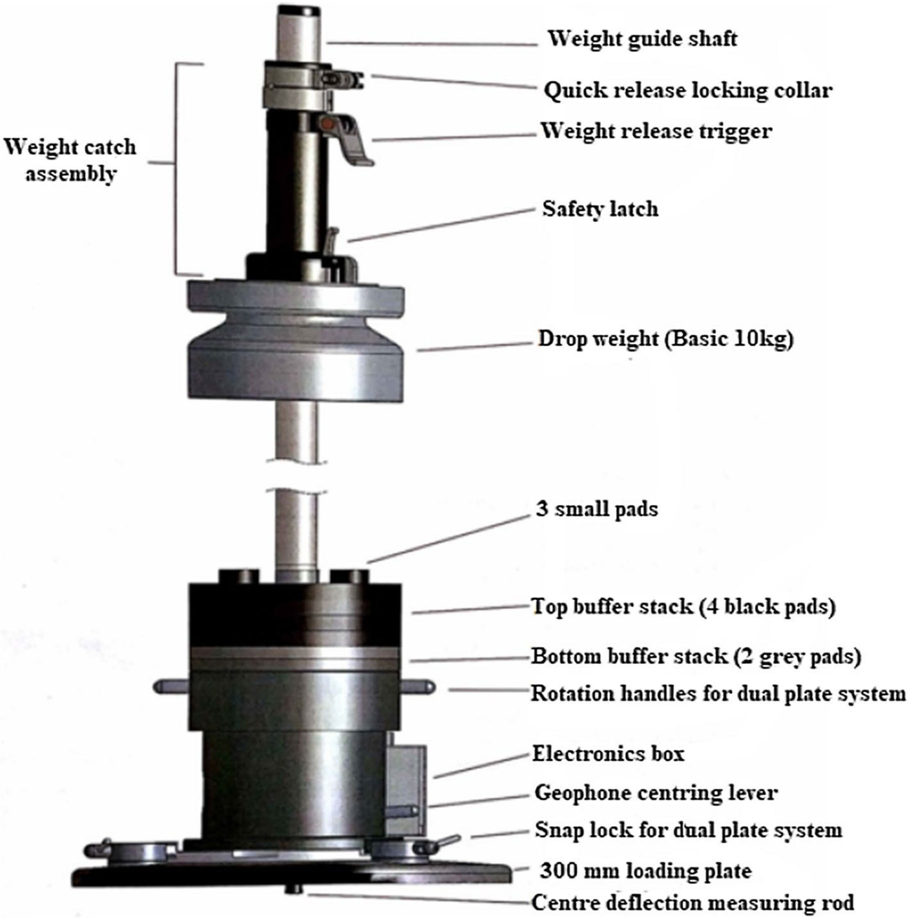


Fig. 2 Light weight deflectometer [41]

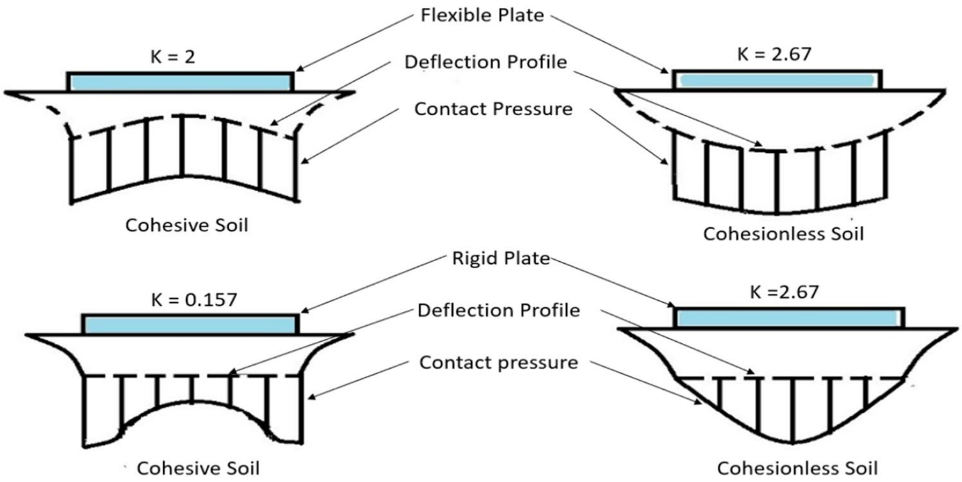


Fig. 3 Contact pressure, Plate deflection profile, and Plate Rigidity factor (K) of flexible and rigid plate [24, 43]

is a sensor attached to the middle of the plate that is used to measure how much deformation has been caused by the plate. An accelerometer is used as the sensor. A stiffness modulus is estimated instantly by the connected software and displayed on the tablet screen after every drop. The display also shows the deflection, the impulse duration, and the rebound deflection. All additional parameters, in particular the contact pressure between the plate and the ground, are assumed to be stable for the estimation of the stiffness modulus. According to the manufacturers' guidelines, LWD tests were conducted using three seating drops and three test drops (Zorn 2003; Dynatest 2004). The LWD modulus is provided for a specific testing point as the average of the last three drops, and it is shown on the PDA (Personal Digital

Table 6 LWD testing range of contact stress level [44]

Test Surface	Level of contact stress (kPa)
Granular base layer	200–300
Subbase layers	100–200
Soil subgrades	50–100
Soft subgrades	10–60

Table 7 Poisson’s ratio value for different material types [33]

Material	Range	Typical value
Portland cement Concrete	0.15–0.2	0.15
Untreated granular materials	0.3–0.4	0.35
Cement treated granular materials	0.1–0.2	0.15
Cement treated fine-grained soils	0.15–0.35	0.25
Lime stabilized materials	0.1–0.25	0.2
Lime-flyash mixtures	0.1–0.15	0.15
Dense sand	0.2–0.4	0.35
Fine-grained soil	0.3–0.45	0.4

Assistant) device. Figure 4 presents the working procedure of LWD. On open-graded aggregate surfaces, however, it was discovered that nine drops were adequate to assure plate seating [47].

The data collected is downloaded to a PC and then, analysed using the LWDmod program, which uses a back-calculation algorithm and requires values such as seed moduli, the thickness of multiple pavement layers, Poisson’s ratio, tyre pressure, and load applied to carry out multiple iterations to finally give the composite and individual layer moduli. Back-calculation is the process of transforming pavement deflections into deformation moduli of the underlying pavement layer. The back-calculation analysis was continued until a root mean square error of less than or equal to 2% was obtained. Different layers are given different moduli values, and estimated deflections from the forward calculation model and measured deflections are compared. The computer program will assume a fresh set of moduli and recalculate the deflections if the differences are too great. Iterative back-calculation is the term used to describe this process. This iterative back-calculation will continue until there is good agreement between the measured and estimated deflections [48]. The LWDmod program also eliminates abnormal observations obtained during the iterative back-calculation to finally give the actual modulus values. Seed moduli values are the approximate standard modulus values of the pavement layers on which the iteration process of the LWDmod program will be based. The back-calculation algorithm shown in Fig. 5 serves as the foundation for the LWDmod software [49].

Geogauge

Geogauge equipment was initially developed by the defence industry to detect land mines. Its ring-shaped foot rests on the soil's surface, and it measures about 10 kg (22 lbs), 28 cm (11 inches) in diameter, and 254 mm (10 inches) tall [3]. With an outer diameter of 4.50 inches (11.4 cm), an inner diameter of 3.50 inches (8.9 cm), and a thickness of 0.50 inches (1.3 cm), it has an annular ring that makes contact with the soil surface [5], as shown in Fig. 6 and Table 8. One test per 1.5 min measures the in situ stiffness of compacted soil [33]. The tool is used for QC and QA to measure how uniform unbound pavement layers are by looking at how stiffness changes across the structure. A Geogauge is used to detect irregularities during construction similar to LWD. Table 9 shows the comparison between LWD and Geogauge.

Principle of geogauge

The Geogauge's basic working principle is to produce a minuscule dynamic force between 100 and 196 Hz. The force produced by the Geogauge was estimated to be 9 N during a laboratory experiment [54]. Geogauge works by causing a minuscule displacement in the soil, less than 0.0005 inches (1.27×10^{-6} m), at 25 steady-state frequencies ranging from 100 to 196 Hz. The stiffness is calculated at each and every frequency, and the mean is displayed. It takes around 1.5 min to complete the process. The Geogauge derives its power from a set of 6 D-cell batteries and is designed not to affect its estimation due to the deflection caused by the equipment operating nearby, as the frequency produced by traffic is about 30 Hz, below the Geogauge’s working frequency

Fig. 4 Working of LWD

Fig. 5 Back calculation algorithm of LWDmod software [50, 51]

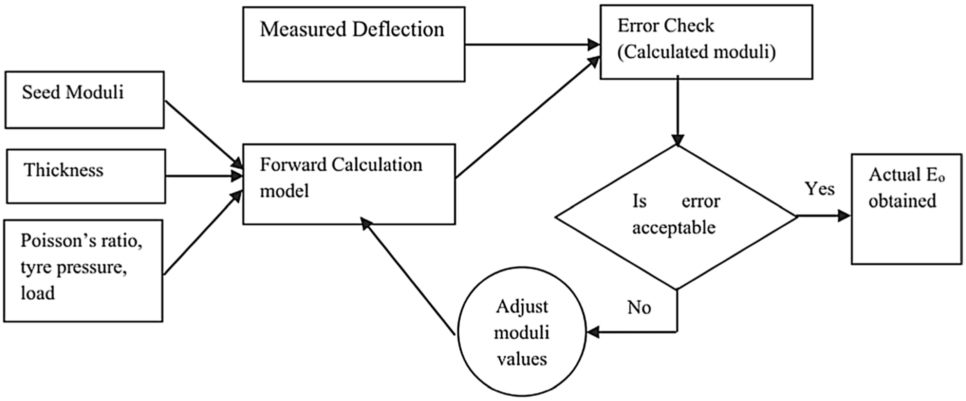


Fig. 6 The Humboldt Geogauge

Table 8 Humboldt Geogauge parameter specification

Parameter	Specification
Time for one test	1.5 min
Weight	10 kg
Diameter	280 mm
Height	254 mm
Outer diameter of annular ring	114 mm
Inner diameter of annular ring	89 mm
Thickness of annular ring	13 mm

(Humboldt Mfg Co. 1999, Geogauge guide). The differential displacement across the flexible plate measured by two velocity sensors is used to calculate the force transferred to the ground, which is applied by the shaker (Fig. 7). This can be expressed as shown in Eq. 2.

$$F_{dr} = K_{flex}(X_2 - X_1) \tag{2}$$

F_{dr} denotes the force applied by the shaker, K_{flex} denotes the stiffness of the flexible plate, X_1 denotes the displacement at the rigid plate, and X_2 denotes the displacement at the flexible plate. Thus, soil stiffness can be calculated using Eq. 3

$$K_{soil} = K_{flex} \sum_1^n \left(\frac{\frac{(X_2 - X_1)}{X_1}}{n} \right) \tag{3}$$

where *n* denotes the number of test frequencies.

Geogauge soil stiffness and modulus calculation

The soil stiffness determined using the Geogauge could be utilised to compute the soil stiffness moduli. The static stiffness, K, of a rigid annular ring on an elastic, linear, isotropic, and homogeneous half-space has the subsequent useful form in Eq. 4 [55].

$$K = \frac{ER}{\left(1 - \mu^2\right)\omega(n)} \tag{4}$$

where E denotes the elastic modulus, μ denotes the Poisson's ratio of the elastic medium, R denotes the outside radius of the annular ring, and ω(n) denotes a function of the ratio of the inside radius and the outside radius of the annular ring. For the ring geometry of the Geogauge, the factor ω(n) is equal to 0.565, thus,

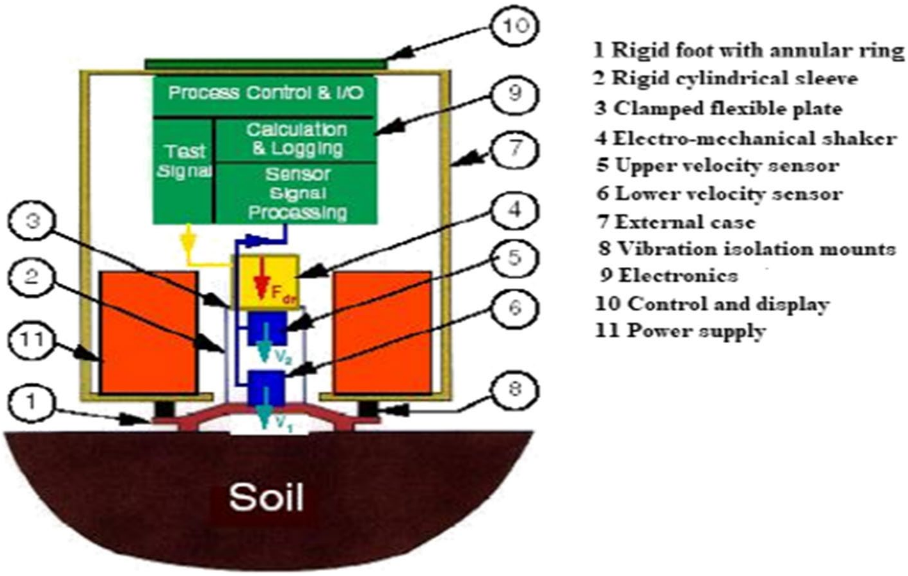
$$K = \frac{1.77ER}{(1 - \mu^2)} \tag{5}$$

Based on Eq. 5, the Geogauge elastic stiffness modulus, or Young's modulus, can be obtained by utilising Eq. 6, projected by CA Consulting Engineers, as follows:

Table 9 Comparison of LWD and Geogauge device [24, 29, 52, 53]

Purpose	LWD	Geogauge
Mode of measurement	Geophone or accelerometer	Velocity (frequency of small dynamic force)
Standards	ASTM E2583	ASTM D6758
Output	Deformation modulus	Modulus
Influence depth	0.9–2 times the plate diameter	220–310 mm
Calibration of device	Required	Calibration plate
Durability	Satisfactory	Satisfactory
Operator skill and training	Moderate	Moderate
Operation	Easy	Easy
Destructive	No	No
Portability	Yes	Yes
Storing data	Yes	Yes
Man power	One	One
GPS	Yes	Yes
Advantages	Rapid results Appropriate for all materials	Quick and non-intrusive Simple to use and very light
Disadvantages	High inconsistency in soft weak soils Rubber pad not suitable below 5˚C Shallow Influence depth	Highly sensitive to seating conditions Shallow Influence depth

Fig. 7 Schematic of the Humboldt geogauge [33]



$$E_G = H_{SG}\frac{(1-\mu^2)}{1.77R} \tag{6}$$

where E_G is the elastic modulus in MPa, H_{SG} is the Geogauge stiffness reading in MN/m, and R is the radius of the Geogauge foot (5.715 cm).

Working

After preparing a levelled surface as mentioned in the Geogauge manual, and then, after the measure button is pressed, it takes around 1–1.5 min to provide the stiffness and modulus values. Then, the average of the three readings is taken as the modulus value of a site location [11]. A detailed description is shown in Fig. 8.

Observation from the literature

Numerous authors have expressed their views on these technologies. Both LWD and Geogauge have been successful in sensing abnormalities in construction conditions, such as decreasing or increasing trends in moduli. It has been observed that Geogauge moduli are consistently higher and rise with LWD moduli. This is due to Geogauge employing low strain in modulus calculations. The ability to detect abnormalities in construction circumstances, such as an upward or downward trend in moduli, was successful for both LWD and Geogauge [57].

In order to determine dynamic deformation moduli (E_{vd}) that are near to resilient modulus (MR), it has been discovered that the necessary number of LWD cycles (repetition) relies on a variety of influencing parameters, including lateral confinement, moisture contents, and the levels of maximum vertical axial stress during testing. It was stated that the cyclic LWD test may be utilised to accurately and reliably anticipate the resilient behaviour of the explored soil in a simple and rapid manner [58]. Additionally, a new testing method has been devised to acquire direct measurements of a compacted geomaterial's resilient modulus (MR) using a straightforward technique. This method was created for both laboratory and in situ testing [17, 58].

The LWD differs from the other equipment in that it estimates structural mechanical response over a larger footprint as opposed to the DCP, which measures the shear strength of soil at a discrete point. It is for this reason that the LWD is attractive for modelling the interaction between vehicles and soils [59].

Regardless of the soil type, it was shown that the modulus falls when measured towards the wet side of the OMC. Particularly vulnerable to the impact of soil moisture were the LWD and Geogauge [60], and when moisture content effects were taken into account, the performance of these instruments improved even more [61, 62]. A field investigation by Afsharikia and Schwartz (2019) revealed a large modulus gain as a result of drying, especially within the first several hours. Due to evaporation, the soil modulus dramatically rose over the first few days (between 3 and 4 days) before stabilising [63]. The findings of a study demonstrated that density had little impact on soil stiffness, but moisture

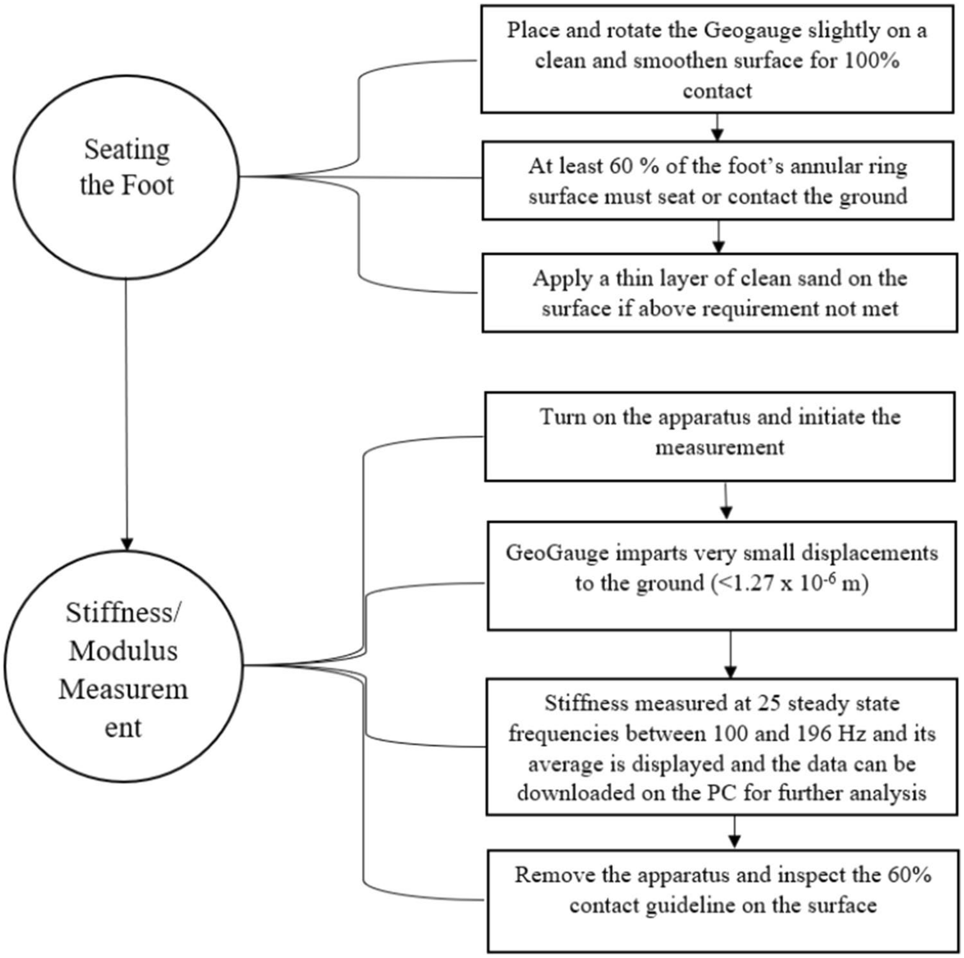


Fig. 8 Working of geogauge [56]

content significantly affected the data from the equipment, particularly the LWD [64].

Based on the tests done for the study, the coefficient of variation of the deformation modulus of the surface and base layers is between 4 and 12%. This means that the LWD test results on the prepared surface and base layers can be thought of as uniform [25].

The stress distribution, due to the applied load of a Light Weight Deflectometer (LWD) on a typical subgrade soil mass, showed that the vertical stresses decreased more quickly in the higher (about 400 mm) part of the soil mass along the centerline. There is a point of inflexion (a point in which the concavity of the function changes) for the change in stress at a depth of around 400 mm. The rates of stress deterioration were found to be much lower after the inflexion point. Within a relatively short area of the subgrade material, the horizontal confining strains significantly dropped along the centre line under the imposed load. The findings showed that the top 300 mm saw the majority of the confining stress degradation. Beyond the point of inflexion, over 95% of the confining stresses decreased, and it was noticed that the levels of stress slightly increased at the container's bottom [65].

The stiffness/modulus determined by LWD remained virtually constant irrespective of the influence of temperature on the buffer. The only change that was immediately noticeable was an increase in the load pulse's duration from 18 to 20 ms as a result of the buffer's rising temperature [66]. Table 10 presents the findings of various authors.

LWD was used to assess the elastic modulus of the pavement surface above an underlying cavity before and after the rehabilitation process and compare it with the elastic modulus of the normal surface near the repair work. The findings showed that, while rehabilitation improved the pavement layer's elastic modulus, it was not entirely recoverable due to the properties of the repair material [81].

An investigation of modified subgrade clay soil mix with steel slag and lime was carried out using a static and dynamic test approach in a laboratory. The static approach involved the laboratory CBR test and the dynamic approach involved LWD testing on top of a CBR mould filled with compacted modified soil. Finally, a 20% increase in modulus was found in 6% lime + 30% Steel slag as compared to 6% lime + 20% Steel slag [82].

In a different study, a modified laboratory LWD called the Laboratory Deflection Measuring Device (AUDL) was developed as a reliable and accurate non-destructive testing tool to measure the modulus of elasticity of various asphalt materials that are asphalt concrete (AC) Base type and AC BC (binder course) type. This modulus was compared to the modulus of elasticity measured on extracted cores using the UMMATA (Universal Material Testing Apparatus) method. The AUDL approach typically yields a lower modulus of elasticity than the UMMATA method. When comparing AUDL with UMMATA, the average modulus value of AC Base material is 7.52 percent lower for AUDL. The average AC BC material modulus value is also 30.93% lower for AUDL. From here, it can be seen that the AUDL and UMMATA approaches have the same pattern [66].

The modulus obtained directly from these tests represented the composite modulus of the layers in cases where the influence depth of the LWD exceeded the thickness of the tested pavement layer, reaching the underlying layers and subgrade. To resolve this issue, the modulus of the tested layer has to be back-calculated using a multilayered system solution [83].

Senseney and Mooney (2010) used the LWD with radial sensors on one and two-layered systems test beds to allay concerns about the LWD's capacity to accurately characterise multilayered soil systems. In the case of stiff-over-soft systems, it was successful in precisely estimating the layered moduli. Through the use of triaxial testing under a similar stress state, a close correlation between E_{LWD} and the elastic modulus values was demonstrated. However, compared to 1.0 to 1.50 for typical LWDs, the measured depth of influence was found to be 1.80 times the diameter of the loading plate. The authors attributed this variation to the availability of radial sensors, which allowed for the measurement of strains affecting deeper materials [35].

A study was conducted to propose a technique for estimating the stiffness of the soil constructed into a road embankment using displacements observed during the LWD test. It was determined that the soil site's dynamic elastic modulus was sensitive to loading and unloading [74]. Another study compared the performance of the Benkelman Beam Deflectometer (BBD) with the Light Weight Deflectometer (LWD) on low-volume roads in order to correlate subgrade moduli using static and dynamic deflection techniques. It was discovered that LWD offers accurate subgrade moduli values and can be utilised as a tool for an immediate evaluation of subgrade strength [84]. The LWD modulus is more sensitive to the structural state of the subgrade surface of the pavement, which leads to a wider range of values because clay shrinks and causes surface cracks [75].

LWD has been implemented as the only compaction QA instrument for unbound materials by the Nebraska Department of Transportation (NDOT) in the US. NDOT also recently developed group indices that can be used to determine the target deflection value depending on the type of soil. The LWD's effectiveness and outcomes have received high marks from NDOT [85].

According to laboratory studies, suction and excessive pore water pressure, respectively, may cause high E_{LWD} to occur at very low and very high saturation levels. A study recommends against using the LWD for building quality control until more study has been done to determine the causes of excessive spatial variability and the impact of

Table 10 Findings of various authors

Devices	Methodology/Material	Findings	References
Geogauge	SM, silty clay, granular subbase material	Repeatable results were produced by the Geogauge They discovered that to translate stiffness values into dry density, they had to create regression analysis for each distinct soil	[67]
Geogauge	Silt with low compressibility	A peak Geogauge stiffness is detected for each compaction effort. These peak stiffness values happen towards the dry side of optimum Soil specimens that have greater stiffness values are inclined to endure more volumetric change upon wetting. Therefore, the soil shrink-swell potential is not optimized if stiffness is	[68]
Geogauge	Silty sand soil	It was discovered that the moisture level that produces the maximum stiffness and density is not the same In silty sand, Geogauge testing showed that stiffness readings varied with soil moisture content	[5]
LWD	Earthwork	When measuring deflections at the ground, LWD devices that employ accelerometers have larger deflection readings than those that use geophones. LWD modulus readings rise as plate diameters are reduced	[69]
LWD	Silty Sand	Readings of the moisture content were correlated with the LWD modulus according to univariate regression analysis	[70]
LWD, Geogauge, DCP	Poorly graded sand with silt	The nuclear density gauge measured dry density, and the findings of the modulus-based tests do not correlate well. If the modulus values from several test devices are directly compared, the findings of the modulus-based tests do not agree that well with one another. This lack of agreement was probably caused by a number of factors, such as differences in the local moisture content and matrix suction conditions, as well as differences in the magnitude and rate of strain applied by the different modulus-based devices	[71]
Geogauge and FWD	Limestone Aggregate	The stiffness modulus calculated using the SSG is well correlated with the dry unit weight (γ_d). The stiffness moduli measured at the same test point for the SSG and the FWD are not correlated	[72]
LWD and FWD	Subgrade with low-plasticity clay	Regression analysis established that LWD is correlated with FWD but doesn't reproduce stiff underlying layers as measured with FWD. The influence depth was superior for FWD than for LWD. Ground stresses were higher for FWD	[73]
LWD	Multi-graded sand and gravel mix built-in embankment	It was determined that the soil site's dynamic elastic modulus was sensitive during the process of loading and unloading	[74]
LWD, FWD, and GPR	Clay of low plasticity, lean clay	The findings demonstrated good agreement in the detection of the abnormal areas between the two NDT techniques (GPR and LWD/FWD)	[75]
LWD	Crushed rock base, soil-aggregate subbase	LWD was discovered to be a rapid tester for the direct and precise measurement of layer moduli and surface deflection for pavement quality assurance	[76]
LWD, DCP	Poorly graded sand with silt and silty sand	The LWD and SSG were predominantly sensitive to the impact of soil moisture, and when the effects of moisture content were taken into account in the analysis, findings for these devices improved considerably	[61]

Table 10 (continued)

Devices	Methodology/Material	Findings	References
LWD	Asphalt Concrete	No significant relation between the International roughness index value and stiffness modulus	[77]
LWD and Geogauge	Open-graded aggregates (OGA)	For all of the studied OGAs, the deformation modulus results generally show an increasing trend as density increases. It appears that the changing modulus of OGAs with increasing density can be properly captured by the LWD and the SSG	[78]
LWD	Siliceous river soil, poorly graded gravel, well-graded gravel, poorly graded sand with silt	The elastic modulus of the well-graded unbound layer was reduced by the incorporation of geogrid (polyester), whereas the effect of geogrid reinforcement on the gap-graded and coarse unbound layers was improved	[19]
LWD, DCP, PLT	Well-graded sand with silt and well-graded gravel	According to experimental findings, the PLT and LFWD assess the equivalent elastic moduli inside the influence zone	[79]
LWD and Repeated load triaxial test	Laterite and non-laterite soils	It was discovered that moisture affects the relationship between LWD and RLT, making laterite soils perform better than non-laterite soils. If RLT testing cannot be carried out, the use of LWD may be an option for mechanical behaviour tests	[80]

moisture content [64]. Other shortcomings include high variability of modulus values from different LWD devices, low repeatability for soft soils, and uneven surfaces.

Test performed on different materials

A road's stiffness will vary depending on the materials used in its construction. These technologies have been applied to many pavement layers, including the subgrade, subbase, base, and surface layer, which are all present in a given area. These include testing on degraded granitic soil subgrade to examine the distribution of stress during LWD tests [65]. For granular roads, the effectiveness of various surface aggregate materials from various quarries, such as Lime Creek Formation Class A, Bethany Falls Limestone Class A, and Oneota Formation Dolomite Class A, has also been compared [92]. The efficiency of field modulus measuring techniques for identifying gravel, limestone, and dolomite quality aggregate material used in construction over weak subgrade was investigated [57]. LWD was used to evaluate the mechanical characteristics of the active layer (thawing soil) in a permafrost scenario [86]. LWD has been used to evaluate the stiffness of compacted subgrade geomaterials such as well-graded silty sand (SW-SM) and well-graded gravel (GW) [79]. Clay-based soft subsurface has been subjected to Geogauge testing for the purposes of evaluating the earthwork [88] and the limestone base course modulus [72]. The resilient modulus of a sandy subgrade has been determined using the cyclic light weight deflectometer test [58]. The deflection and stress behaviour of an interlocking concrete block pavement was also studied using LWD and Geogauge [95]. For poorly graded calcareous and siliceous sands, a light weight deflectometer has been employed to evaluate the degree of compaction on the spot [53]. In a research study, two laboratory asphalt slab specimens and an as-built pavement were subjected to light weight deflectometer (LWD) testing. The experimental findings were compared with the prediction master curve modulus [96]. For performance-based pavement foundation design, LWD evaluated coarse granular materials such as crushed concrete, mudstone, sand, and granodiorite [97]. For the purpose of preventing compaction, tests on sandy loam were conducted to determine the relationship between soil stiffness, dry density, and saturation level [98]. With the use of continuous compaction control and site-specific in situ experiments, LWD and Geogauge were utilised to evaluate poorly graded sand with silt (SP-SM) and silty sand (SM) soil compaction [61]. Tables 11 and 12 list several materials and the range of their moduli.

However, these deformation modulus values for different materials cannot be generalised as they may vary depending upon various other factors like moisture content, type of equipment, and thickness of the underlying structure. Hence, before every construction activity, a test pad of the required road standard has to be built to determine the optimum modulus range. According to the survey, the majority of LWDs operate similarly and use the same testing procedures. However, because of the various applied stresses and deflection measurement procedures, there are variations in the calculated E_{LWD} values [34, 69]. The LWDs that measure the deflection of the loading plate using accelerometers,

Table 11 Compacted Geomaterials with a range of elastic modulus (E_{LWD}) using LWD

Material	E_{LWD} (MPa)	References
Silty sand/Silty gravel	15–42	[86]
Poorly graded sand with silt	30–120	[70]
Weak soil subgrade (CBR = 6%)	48–180	[57]
Bituminous surface layer	587–635	[87]
Decomposed granitic soils	80–120	[65]
Clay	4–21	[88]
Base–Crushed Limestone (Well-graded gravel))	105–122	[89]
Cement–bitumen-treated materials (1 Hour to 90 days)	150–1800	[23]
Poorly graded silty sand (SP-SM)	12–43	[61]
Clay of low plasticity (CL)	50–102	[75]
Crushed rock base	170–1794	[76]
Soil-aggregate subbase	64–730	[76]
Low-plasticity clays	4.07	[90]
Low-plasticity clayey sand (CL-SC)	3.61	[90]
Clayey sand (SC)	3.53	[90]
Sandy soil	36–187	[91]
Lime creek formation class A	128	[92]
Bethany falls limestone class A	85	[92]
Oneota formation dolomite class A	121	[92]
Low-plasticity silt (ML)	70	[93]
Silty sand (SM)	41	[94]
Clayey sand (SC)	41	[94]
Well-graded silty sand (SW-SM)	50	[94]
Low plasticity silty clay (CL-ML)	23	[94]
Well-graded silty sand (SW-SM)	48	[79]
Well-graded gravel (GW)	39–42	[79]
Sandy subgrade soil	60–350 MPa at 3% moisture 40–250 MPa at 4% moisture content	[58]
Interlocking concrete block pavement	115–144	[95]

like the Zorn LWD, reported greater deflections than the LWDs that measure ground surface deflections (e.g. the Dynatest LWD). As a result, when a 300 mm plate diameter was employed, the moduli calculated by Dynatest and Keros LWD were, on average, 1.7 and 1.75 to 2.16 times bigger than the moduli estimated by Zorn LWD, respectively [99]. Thus, *the modulus* has to be determined for the pavement layers' geomaterial in every particular construction work. These values could provide an approximate idea of the range of moduli for carrying out QC/QA work, but they are not absolute. Further research is required to develop better specifications for different types of materials.

Table 12 Compacted Geomaterials with a range of elastic modulus (E_G) using Geogauge

Materials	E_G (MPa)	References
Weak subgrade (CBR = 6%)	76–190	[57]
Poorly graded sand	45–70	[72]
Silty sand	55–250	[72]
Silty sand (SM)	87.36	[100]
SP (Poorly graded sand)	49.33	[100]
Well-graded silty sand (SW-SM)	28.75	[100]
Soft soil (Clay)	25–95	[88]
Base–crushed limestone (GW)	114–136	[89]
Subgrade- High plasticity clay (CH)	145–160	[89]
Poorly graded silty sand (SP-SM)	20–100	[61]
Sandy SOIL	42–176	[91]
Subgrade (silty sand)	48–69	[101]
Interlocking Concrete Block Pavement	105–131	[95]

Test performed on reinforced soil

There are several studies on these modulus-based technologies for QA/QC of non-reinforced pavement layers. There have been few studies on stabilized, modified, or reinforced pavement layers [102]. LWD has been used to assess the strength and durability of a lignosulfonate-treated ML soil subgrade in situ [103], as well as the effect of active fillers such as cement and lime on the in situ performances of foam bitumen stabilised mixes [104]. Geogauge has been used to assess the coir geotextile-reinforced silty sand subgrade for low-volume pavements [101, 105], as well as the field and laboratory performance of cold-region sand stabilised with Geo fibre and synthetic fluid [106]. LWD was used to assess the mechanical performance of cement–bitumen-treated materials in laboratory and in situ tests [23]. LWD was used to investigate further stabilising strategies, such as the use of organosilane and lignosulfonate for crushed rocks like green schist and gabbro for unbound road layers [107]. The performance of polyester geogrid-reinforced unbound layers [19] and flexible pavement systems comprising geocomposite (non-woven polypropylene fibres) [108] drainage layers employing Light Weight Deflectometer has been studied in the laboratory.

These devices have been able to record and determine the increase in stiffness/modulus over time due to the curing of non-conventional materials. This increase in modulus could be due to physical reinforcement like geosynthetics and geogrid, or it could be due to the formation of precipitate in the voids, resulting in increased density during chemical stabilization. To determine the effectiveness of employing the LWD to analyse the stiffness qualities of these materials, Abu-Farsakh et al. conducted extensive laboratory and field testing using the LWD on various types of geomaterials. They looked at how E_{LWD} for soils with 2% and 4% cement concentrations changed over time after compaction. Due to significant standard deviations, the trend for change in E_{LWD} over time, however, was not obvious [83]. Further research is required to develop better specifications for the use of these devices on stabilised materials. Figure 9 shows the modulus improvement of several modified compacted materials.

Repeatability of modulus/stiffness-based testing devices

The repeatability of the LWD measurement has a significant impact on its reliability. When one evaluator uses the same measuring tool repeatedly to test the same characteristic on the same spot, repeatability is defined by variations in measurement [110]. Figure 10 displays the findings of a study that assessed the repeatability of the data from two different compaction testing techniques. In the first method, initial tests were run on each device, and then, 5–10 more tests were run without removing the compaction test device. The second method entails removing the compaction test equipment, replacing it, and then starting a fresh test. This technique is essential since it measures the tested devices' precision. If a device cannot demonstrate a sufficient level of repeatability, it cannot be regarded as a viable choice [109]. Figure 10 shows that the E_{LWD} (modulus) value is the basis for the precision uncertainty. Table 13 displays the

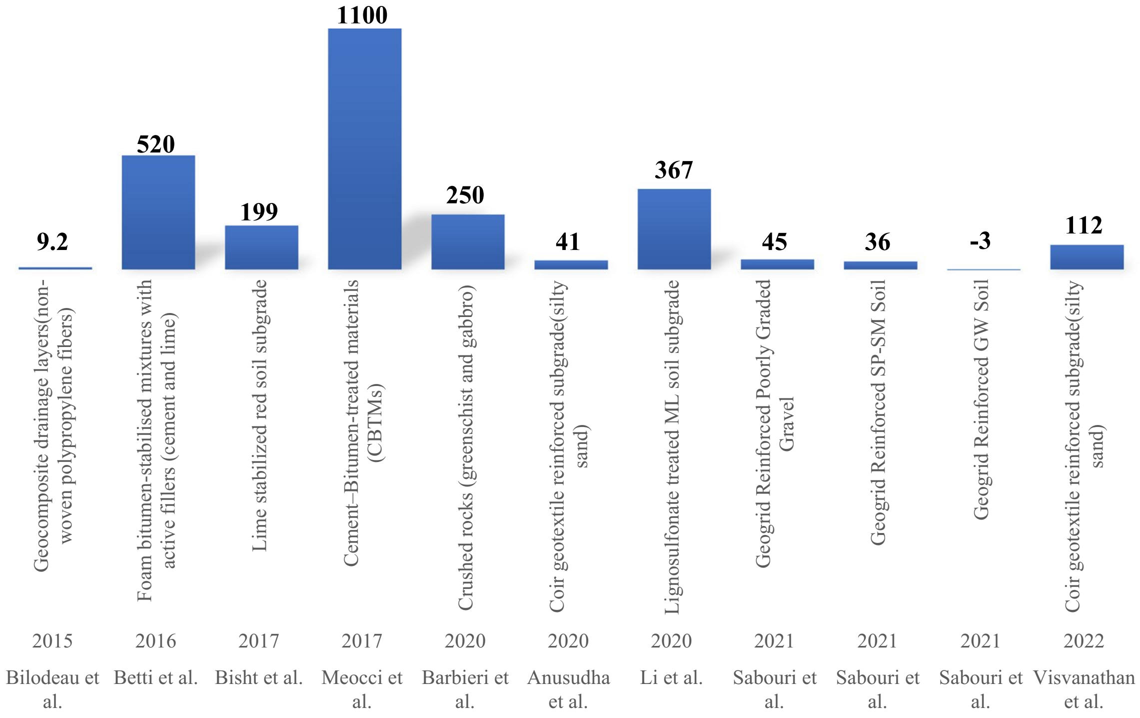


Fig. 9 Graph showing modulus improvement (%) in reinforced/stabilized soil

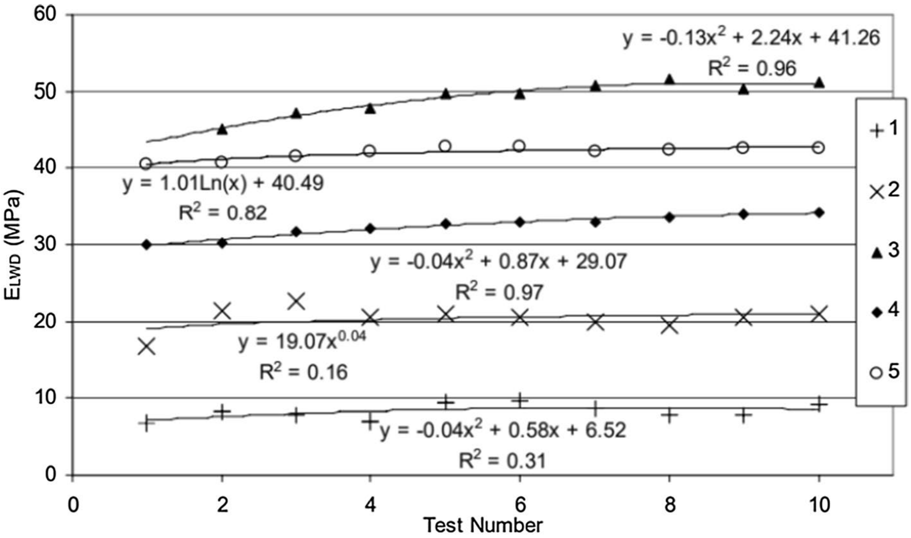


Fig. 10 Repeatability of modulus values in various soils using LWD [109]

Table 13 Data summary

Series	Average E_{LWD}	Uncertainty of 2σ	Uncertainty of 2σ (%)
1	8.21	1.73	21.02
2	20.40	2.54	12.43
3	49.25	0.85	1.72
4	32.72	0.50	1.52
5	42.19	0.70	1.66

uncertainty values of Fig. 10 to within two standard deviations. This shows that E_{LWD} values of at least 30 MPa are needed for uncertainty in the precision of less than 2%.

In a different investigation, the coefficient of variation (COV) of the five measurements that were made at each test section was used to assess the repeatability of the LWD device. As the LWD deformation moduli increased, it was noticed that the COV values decreased. The difficulty of conducting LWD tests on weak subgrades was also discovered during field testing. The reason is that conducting the LWD test on a particularly weak subgrade typically results in permanent plastic deformation, which further compacts the soil. On the other hand, stiffer and well-compacted pavement layers improved LWD performance [20]. According to Fleming [8], comparable conclusions were reached. His research showed that field tests with LWD and FWD on soft subgrade materials were more different than those with stiffer subbase and base course materials. However, there was low repeatability for soft soils and uneven surfaces.

A big soil bin filled with sand and silt was used to test the Humboldt Geogauge's repeatability by doing so three times in a row at the same depth, then doing it again for a total of six measurements (8 ft. in depth and 15 ft. in diameter). The six readings were taken for four different soils at five to seven different depths. A standard deviation was calculated after averaging the first three readings. The second set of three readings was finished along with this. From the observations, it was determined that the Geogauge provided admirable repeatability with consecutive measurements [67]. However, the repeatability of measurements was difficult to achieve in some instances [111].

Statistical limits of modulus/stiffness

To conduct a proper QC/QA, the setting of statistical limits for either deflection or deformation modulus must be done in advance. Test pads are constructed to determine the maximum deflection or minimum deformation modulus corresponding to the required dry density or maximum dry density [22, 25, 112, 113]. A control chart is a vital method to carry out the acceptance or rejection of any parameter at a location. A typical control chart consists of an upper control limit (UCL), a mean, and a lower control limit (LCL). The parameters falling above UCL and below LCL are rejected, and those between them are accepted [28].

Also, standard target values (TV) are set corresponding to a test pad, which is the minimum value of modulus to be achieved. In a study to evaluate the performance of lime stabilised subgrade soil using LWD, the degree of compaction for LWD moduli less than 25 MPa is below 97%, a correlation that is not appropriate for subgrade stability as per the Indian National Rural Roads Development Agency (2007) [18]. So, a target value of 25 MPa was suitable. In a different study, an analysis of the data showed that there are target values for E_{LWD} that could replace the present 95% density criterion. Consistent TVs resulted from test beds, and numerous sites, including Class-1 backfill soils. The TVs for E_{LWD} that were observed were found to be

32.5 MPa. Within the range of the data, there was no difference between the TVs in the different Class-1 backfill soils. Figure 11 shows a target value in a graphical form for LWD meeting 95% compaction (with %C implying percent compaction) [109]. In another study, Farrag et al. (2005) gave Geogauge stiffness target values for sand and silty-clay as 33.88 MN/m and 50.8 MN/m, respectively, corresponding to 90% relative compaction [114]. Modulus-based quality assurance specifications were developed in a study that can be put into practise by state DOTs. They suggested using the LWD test to ascertain the field target modulus on the Proctor compaction mould [64].

There is also a concept based on maximum allowable deflection (MAD). The unique concept calls for a maximum allowable deflection value to be found by running a roller over a test section over and over again until the difference in deflection between two successive passes does not exceed 0.02 mm. Five roller passes are recognised as the minimum number of passes. The MAD for the specific material is the average of the 10 LWD tests, and this value is used as the target of the project [22, 112, 115]. Table 14 displays the MAD of various soil types.

Table 14 Maximum allowable deflection [115]

Material type	Maximum allowable deflection (mm)
Lime-modified soil	0.30
Cement-modified soil	0.27
Aggregates over lime-modified soil	0.30
Aggregates over cement-modified soil	0.27

Control charts for QA/QC

Shewhart control charts, or c-charts, are an additional alternative used in the quality control/assurance process [117]. In this c-chart of quality control/assurance, using the mean of a given procedure, the lower control limit (LCL) and the upper control limit (UCL) are identified using the standard deviation of a sample, as shown in Fig. 12. When the mentioned values begin to fall outside the control limits, the system is understood to be out of control, and action must be taken to bring the system back to a state of control. The universal model for a control chart involves the selection of upper and lower control limits. The upper control limit (UCL), centerline (CL), and lower control limit (LCL) are shown in Fig. 12 and Eqs. 7, 8, and 9, respectively.

$$\mathrm{UCL} = \mu + k\sigma \tag{7}$$

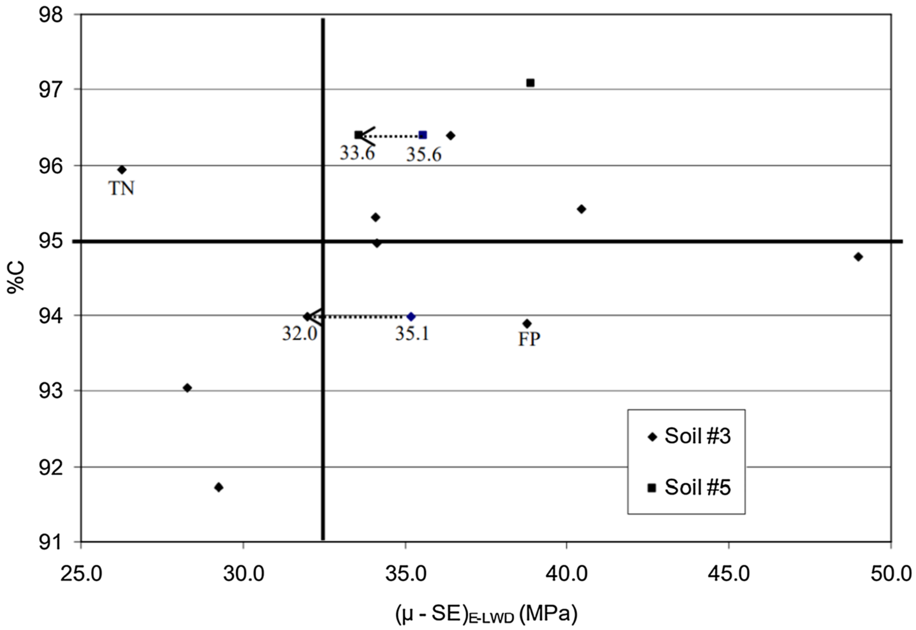
$$\mathrm{CL} = \mu \tag{8}$$

$$\mathrm{LCL} = \mu - k\sigma \tag{9}$$

where k represents the distance of the control limits from the centreline/mean, articulated in standard deviation units.

There are two common sets of limits. The inner limits are known as the warning limits and are typically set at 2σ, while the outer limits are known as the action limits and are typically set at 3σ. The system is deemed to be out of control when values begin to exceed the warning limits, although

Fig. 11 Target Values for Modulus using LWD [109]



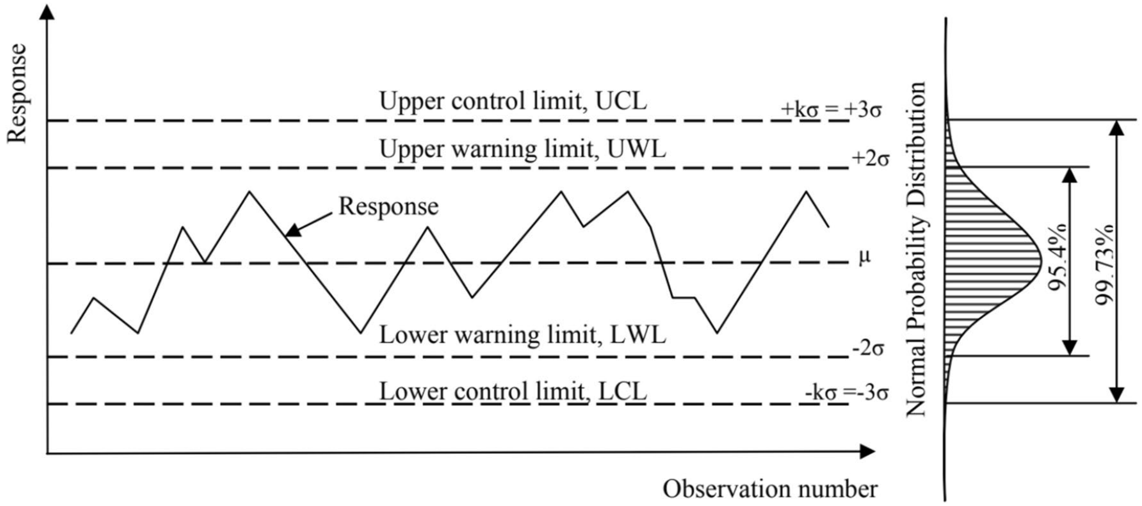


Fig. 12 Representative control chart showing the limits [116]

until results are outside the action limit, no action will be taken to bring the system back under control [116].

These control charts could show the limits of modulus values, resulting in acceptance/rejection of the quality based on whether the modulus value lies within or outside the limits.

Established applications and correlations

LWD and Geogauge are used to determine the various physical properties of different pavement layers. LWD has been used to study the behaviour of soil during vibratory compaction to aid in the development of continuous compaction control [121] as well as for the evaluation of the strength of chemically modified subgrades with time [103]. LWD and Geogauge have been used to differentiate between different quality aggregate materials used in unsurfaced pavement construction [57]. A study was conducted where, to assess the compaction quality, a test section was first constructed with proper guidelines, and maximum allowable deflection values or statistical limits were set to evaluate the compaction quality of the pavement layers of the project so as to accept or reject the construction quality if LWD deflection values were out of limits [22].

It has been studied how LWD correlates with tested soil properties like dry density, CBR, resilient modulus, etc. It has also been studied how E_{LWD} correlates with various in situ test moduli, such as FWD, plate load test, and DCP. It has been determined that the LWD can be used to describe the stiffness of subgrade soils if the soil is in the elastic range. With the modulus increasing, the COV dropped [83]. It was found that E_{LWD} is highly correlated with FWD back-calculated resilient modulus (M_{FWD}), plate load test (PLT) stiffness moduli (E_{PLT}), UCS, and CBR. However, the correlation between E_{LWD} and dry density was not found to be significant.

Geogauge has been applied for the evaluation of coir geotextile-reinforced subgrade [101, 105] as well as for earthworks assessment [88]. LWD has also been used to establish the resilient modulus of fine-grained soil [94] and to assess the performance of stabilised mixtures [104]. These devices can be used on pavement structures containing geocomposite drainage layers [108], geogrid-reinforced layers [19], and concrete block pavement [95]. LWD has been used to determine the degree of compaction [53] as well as to assess the moisture effect on the moduli of pavement [120]. LWD provides a non-destructive method for the predictive master curve of asphalt pavements [96]. These technologies can be used to estimate CBR, and dry density [33, 67, 122]. A proposed LWD-based method was also found to be a good way to estimate the in situ shear strength characteristics of the compacted soil subgrade [123]. The correlation of Geogauge with tested soil properties like dry density, CBR, resilient modulus, etc., has been determined. It has also been studied how E_G correlates with various in situ test moduli, such as FWD, plate load test, and DCP. It was found that E_G is highly correlated with FWD back-calculated resilient modulus (M_{FWD}), plate load test (PLT) stiffness moduli (E_{PLT}), UCS, and CBR. The empirical or regression correlations developed between the LWD and Geogauge obtained modulus and other equipment and material properties are shown in Tables 15 and 16.

The correlations developed can be used by the practitioners for obtaining the relevant properties of the pavement layers, but these correlations are very specific to a particular geomaterial, type of equipment, and design standards and cannot be generalized. Therefore, further research is needed to develop correlations and specifications for different types of materials.

Critical review of these devices

The range of modulus presented in the paper is very specific to the type of geomaterial, which may vary from site to site, seasonal variations, equipment type, and thickness of the underlying layers according to design standards. So, it is difficult to specify standard deformation values. Hence, before every construction activity, a test pad of the required road standard has to be built to determine the optimum modulus range. There is very less work available on stabilized pavement layers to significantly evaluate and develop specifications for the response of these devices on modified materials. The other limitations include the shallow depth of influence of both of these devices. Also, the results can be inaccurate if proper seating of the equipment on the surface is not ensured. Geogauge applies a very small load that does not mimic the actual traffic load. According to laboratory studies, suction and excessive pore water pressure, respectively, may cause high E_{LWD} to occur at very low and very high saturation levels. Researchers endorse using these devices for compaction quality control but highlight the impact of excessive spatial variability and moisture content on the modulus values obtained from the devices. Other shortcomings include high variability of modulus values from different LWD devices, low repeatability for soft soils, and uneven surfaces. Some studies have been done on the modulus determination of lateritic subgrade soil. However, there is hardly any study on the modulus behaviour of alluvial soils in India using these NDT devices.

Conclusion

The construction of modern highways requires great attention in terms of quality in order to ensure long-term performance. Non-destructive testing is more efficient than

Table 15 Regression/Empirical correlations between LWD obtained modulus and other equipment/material properties

Evaluated Geomaterial	Correlations	R^2	References
Volcanic soil, silty sand, and mechanically stabilized crushed stone	$Log\left(\frac{K_{LWD}}{K_{30}}\right) = 0.0031\log\left(K_{LWD}\right) + 1.12$	–	[118]
Silty and clayey-type soil	$E_{PLT(i)} = 0.907*(E_{LWD}) - 1.8$ $E_{LWD} = 2191/PR$	0.844 0.716	[31]
Granular and fine-grained soils	$E_{PLT(i)} = 0.71E_{LWD} + 18.63$ $E_{PLT(R2)} = 0.65E_{LWD} + 13.8$ $M_{FWD} = 0.97E_{LWD}$	0.87 0.87 0.94	[83]
Crushed Limestone	$CBR = -14 + 0.66(E_{LWD})$	0.83	[33]
Lateritic Subgrades	$CBR = -2.754 + 0.2867E_{LWD}$	0.90	[119]
Lateritic Subgrades	$E_{LWD} = 162.48 * (DCPI)^{-0.6398}$	0.73	[39]
Granular pavement foundation layers	E_{FWD} (MPa) = 99.88 + 0.50 E_{LWD} (MPa)	0.24	[34]
Subgrade with low-plasticity clay	$E_{LWD} = 6{,}680 \ln (E_{FWD}) - 48{,}429$	0.783	[73]
Cement–bitumen-treated materials	$E_{LWD} = 385.58 \, (days)^{0.342}$	0.982	[23]
Lime Stabilized Red Subgrade Soil	$UCS = 4.9 \, E_{LWD}$ $CBR = 0.15 \, E_{LWD}$	0.99 0.93	[18]
Sandy Soil	$(CBR)_{US} = 0.0009(E_{LWD})^2 - 0.064E_{LWD} + 6.904$ $(CBR)_S = 0.0001(E_{LWD})^2 - 0.0015E_{LWD} + 1.184$ $\rho_d = 1E - 05(E_{LWD})^2 + 0.002E_{LWD} + 1.098$	0.807 0.805 0.770	[91]
SM, SC, SW-SM, CL-ML	$SM_R = 0.97 \, (E_{LWD,MOLD})$	0.82	[94]
SW-SM and Well-graded gravel	$E_{vd} = 0.636 \, G_{max}$	–	[79]
Interlocking concrete block pavement	$E_{PLT} = 6.255 \, E_{LWD} - 519.79$	0.763	[95]
Unbound aggregates base	$E_{LWD} = 0.001 \, RRM^{2.29}$	0.65	[120]

K_{LWD} is the ratio of stress on LWD loading plate to the measured deflection at that stress. K_{30} is the ratio of stress on plate with 300 mm diameter for a PLT to the measured deflection at that stress. $E_{PLT(i)}$ is initial elastic modulus in MPa, and $E_{PLT(R2)}$ is reloading moduli estimated by PLT test. PR is penetration rate of Dynamic cone penetrometer. M_{FWD} = resilient modulus back-calculated from FWD. DCPI is dynamic cone penetration index. E_{FWD} is elastic modulus obtained using falling weight deflectometer. UCS is unconfined compressive strength. CBR_{US} and CBR_S is unsoaked and soaked California bearing ratio values, respectively. ρ_d is dry density. SM, SC, SW-SM, CL-ML are USCS soil classification names and stands for silty sand, silty clay, well-graded sand with silt and low compressible silty clay, respectively. SM_R is summary resilient modulus. G_{max} is maximum shear modulus. E_{vd} is dynamic deflection modulus of the subgrade. RRM is the representative resilient modulus

Table 16 Regression/Empirical correlations between Geogauge obtained modulus and other equipment/material properties

Evaluated Geomaterial	Correlations	R^2	References
Subgrade materials	$M_{FWD} = 37.65H_{SG} - 261.96$	–	[32]
Crushed Limestone	$CBR = 0.00392 * \left(E_G\right)^2 - 5.75$	0.84	[33]
Silty and Clayey-type soil	$\log\left(E_G\right) = 1.277 + 0.675\log(CBR)$ $E_{PLT(i)} = 15.5*e0.013(E_G)$ $E_G = 755.2*(PR)—0.671$	0.62 0.83 0.517	[31]
Granular soils	$M_R = 20.3 * (E_{Geo})\ 0.54$	0.83	[124]
Sand, crushed limestone, gravel	$CBR = 0.00392 * \left(E_G\right)^2 - 5.75$ $E_{PLT(i)} = -\ 75.58 + 1.62*E_{G,}$ $E_{PLT(R2)} = -\ 65.37 + 1.50*E_G$	0.84 0.87 0.9	[83]
Poorly graded sand, silty sand	$E_G(MPa) = 0.0018(\gamma_d)^{3.76}$	0.821	[72]
Soft clay	$E_G = -0.3253\ w^2 + 6.9571w + 43.536$	0.906	[88]
Sandy soil	$(CBR)_{US} = 0.001(E_G)^2 - 0.124E_G + 9.342$ $(CBR)_S = 0.0002(E_G)^2 - 0.014E_G + 1.703$ $\rho_d = 2E - 05(E_G)^2 + 0.001E_G + 1.119$	0.798 0.793 0.73	[91]
Interlocking concrete block pavement	$E_{PLT} = 12.67e^{-0.0225E}{}_{Geo}$	0.849	[95]

H_{SG} is the Geogauge stiffness reading articulated in MN/m. M_{FWD} is FWD back-calculated modulus in MPa. M_R is resilient modulus. $E_{PLT(R2)}$ is the reloading modulus. w is moisture content

destructive testing since it allows for quick measurement and analysis of relative data for quality maintenance on a specific section of a highway. The paper presents a comprehensive review of non-destructive testing using LWD and Geogauge in relation to the construction QC and QA of pavement layers.

There is a proper distinction between stiffness and modulus because stiffness refers to the quality of a structure and modulus refers to the quality of a material.

It was found that the use of said devices is advantageous over NDG as well as destruction testing methods. It also produces results quickly, which can be noticed during measurement for immediate action on the material's quality.

The loading plate diameter, applied stress, plate rigidity factor, and Poisson's ratio are the variables affecting the deformation modulus. The required stress must be obtained by adjusting the plate diameter and drop height because they are fixed with respect to the various layers.

The range of the target modulus is to be determined after preparing a test pad on-site for fixing a base value that will be used as a reference for subsequent measurements and judgement.

There is a good correlation between the deformation modulus and standard tests, such as the UCS, CBR, and moisture content, using both devices, in an effort to cut the testing time by a large amount. However, the correlation between dry density and CBR is not so significant. These devices have also been able to record and determine the increase in stiffness/modulus over time due to the curing of non-conventional material.

They also revealed a high degree of spatial variability and a considerable impact of moisture content on the modulus values, which is one of the main problems with modulus-based devices. To get accurate and repeatable data for the development of LWD specifications, additional factors such as pavement layer qualities and LWD type should be taken into account. The repeatability and reproducibility of these modulus-based devices need to be improved through further study. More research should be carried out to determine the influence of moisture content on modulus values for different types of materials.

Modulus-based compaction QC/QA of unbound materials is gaining popularity in the USA; however, these devices are seldom ever used in India. These tools can be used effectively to judge the degree of compaction of the pavement layers. These tools enable the long-term performance of roads in developing nations like India.

Future studies

The majority of work done using these devices was done on locally available materials, and the performance was satisfactory. However, there is limited work on locally available soil or stabilised soil, that is, alluvial soil in Bihar, India. There is a lot of research on correlations between deformation modulus and tests like UCS, dry density, CBR, and moisture content for locally available (conventional) materials, but less for the region of Bihar, India. More studies can determine stiffness Target Values (TVs) for different material types and pavement layers. Very little research has been done to ascertain the shear strength parameters of subgrade soil using FWD and LWD, but not with Geogauge. In this area, research is possible. Modulus-based degree of compaction QC/QA method should be developed. With these technologies, more research can be done on subgrade soil that has been modified with stabilising agents other than those already used.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Ethics approval Ethics approval was not required for this systematic review.

Informed consent Informed consent was not required for this systematic review.

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