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Quality Assessment of Road Shoulders using Light Weight Deflectometer and Geogauge

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Abstract: *Shoulders are an important element of the highways that provide space for vehicles to stop during an emergency. A well-compacted shoulder provides structural firmness to a pavement by transferring overlying traffic loads to the underlying soil stratum. They provide lateral support to the pavement. In recent years, the use of non-destructive testing devices like Geogauge and Light Weight Deflectometer (LWD) has emerged in our country. The main reason behind this is the inbuilt ability of Geogauge and LWD in the fast estimation of the elastic modulus of a shoulder on top of their ease to port, being cost-effective, the capability to give more amounts of data, etc. Thus, there is a need to assess these devices. The main objective of this paper is to develop correlations between the parameter obtained from these non-destructive devices and destructive test parameterslike dry density and CBR. The tests were conducted on thirty-two locations of road shoulders at the city of Patna, India. Geogauge, LWD and sand replacement or sand cone testing were performed at different locations and soil samples were collected for determination of CBR and water content in the laboratory. The result of regression analysis shows that a significant correlation exists between moduli obtained from the devices under investigation and standard test results i.e. dry density and CBR. These developed correlations may be used by the road engineers for assessment of the quality of the shoulders.*

Keywords: ***CBR,Dry Density, Elastic modulus, Geogauge, LWD.***

I. INTRODUCTION

Compaction of shoulders of pavement influences its durability and stability. A well-compacted shoulder is important for a long lasting bituminous or concrete pavement as it provides lateral support to pavements as well as gets utilized as an emergency lane especially during rush hours. In India, highway shoulders are generally unpaved. They are deteriorated over time due to the erosion of soil by rainwater and the rubbing action of vehicle wheels. This creates a level difference between surfaces of pavement and shoulder as they are not maintained or repaired on time. This causes unsafe driving of vehicles during an emergency or overtaking operation on shoulders. Accidents may also be caused due to soft shoulders. Thus, periodic quality assessment is required. After compaction of soil shoulder on ground level or embankment, for proper quality control (Q/C) or quality assurance (Q/A) or for determination of the quality of compaction various tests and methods are used. The conventional methods for measurement of density are core cutter, and sand replacement (sand cone) which are time taking, destructive, labor-intensive whereas nuclear density gauge is hazardous. While for the determination of the strength of soil subgrade or shoulders,
CBR tests are performed in the laboratory which is also destructive, time taking and labor intensive. Therefore, these are not efficient methods to gather a huge amount of data. Nowadays, Dynamic cone penetrometer (DCP) is also used to determine field CBR indirectly.

In developing countries like India apart from the use of well-established traditional evaluation techniques such as the California Bearing Ratio (CBR) test and the dynamic cone penetrometer test, the use of nondestructive testing devices such as the Light Weight Deflectometer (LWD) has gained popularity in recent years. This is mainly because of the inherent capability of LWD in obtaining quick estimates of the modulus of subgrade in addition to their simplicity in design and portability [1]**.** The same can be said about Geogauge.Thus, there is a need to correlate the results of LWD or Geogauge with soil properties like dry density and CBR to obtain these values indirectly.

Ferreira et al. [2] measured dry density (γ_d) and the stiffness modulus (E_G) using nuclear density gauge and Geogauge respectively. A model was developed between dry density and stiffness modulus (elastic modulus) as given in(1). It was reported that the development of reliable and easy procedures for the in-situ stiffness modulus evaluation of granular pavement layers using lightweight equipment of moderate cost such as Geogauge has great advantages with significant savings in cost and time.

$E_G(MPa) = 0.0018\,(\gamma_d)^{3.76}$ (R^2 = 0.821) (1)

Nazzal [3] evaluated the feasibility of using Geogauge, Light Weight Deflectometer (LWD), and Dynamic Cone Penetrometer (DCP) devices to measure in-situ stiffness modulus of constructed highway layers and embankments. A comprehensive regression analysis on the collected field test results was carried out to develop the best correlations between CBR values and stiffness modulus values obtained from Geogauge (E_G) and LWD (E_{LWD}). The relevant models developed are given in(2) and (3).

$CBR = 0.00392 * (E_G)^2 - 5.75$ (R^2=0.84) (2)

$CBR = -14 + 0.66\,(E_{LWD})$ (R^2=0.83) (3)

Seymen [4] carried out an evaluation of in-situ tests like Geogauge, LWD, and DCP in the laboratory. Test layers were prepared in two boxes that measure 5 ft length x 3 ft width x 2 ft depth at Louisiana Transportation Research Center. Correlations were developed between the results of these devices with CBR value as given in(4) and (5).

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There was no significant correlation found between E_{LWD} and CBR whereas E_G correlated better with the CBR.

$\log(E_G) = 1.277 + 0.675 \log(CBR)$ (R^2=0.62)(4)

$\log(E_{LWD}) = 1.149 + 0.702 \log(CBR)$ (R^2=0.36)(5)

Alshibli et al. [5]assessed the potential use of LWD and Geogauge as quality control devices for subgrade, base course and compacted soil layers. Good statistical correlations were found between elastic moduli measured by the devices used in this investigation.

Powell et al. [6]developed a correlation between the CBR and the elastic modulus of subgrade obtained using LWD. The model developed is given in(6).

$$E_S = 17.58\, CBR^{0.64} \quad (6)$$

George et al. [1] developed LWD, Dynamic Cone Penetrometer (DCP), and CBR correlation for evaluation of lateritic subgrades. It was observed that the dry density has a significant influence on the estimation of CBR and E_{lwd}values. **Singh et al.** [7]proposed a correlation of CBR with elastic modulus obtained using LWD. The model developed is given in(7). The model proved to be an efficient and valuable aid in the in-situ testing of compacted soil layers.

$$CBR = 0.0091\,(E_{mod})^2 - 0.5191\,(E_{mod}) + 15.982$$
$$(R^2 = 0.841) \quad (7)$$

Bilodeau and Dore [8] tried to evaluate stress distribution measured under an LWD loading plate. It was found that the stress distribution factor was appreciably affected by the loading plate diameter. **Gosk** [9] tried to present a method to determine the stiffness of the soil built-in road embankment on the basis of the LWD test using displacements recorded at the time of impact test. The sensitivity of the dynamic elastic modulus of the soil site during the course of loading & unloading was established. **Marecos et al.** [10] assessed the pavement subgrade by combining diverse nondestructive methods. Different GPR systems were utilized to spot subgrade cracking along with FWD (Falling Weight Deflectometer) and LWD to detect damaged areas. Good conformity existed between both nondestructive methods in the detection of problem areas. **Guzzarlapudi et al.** [11] conducted relative studies of LWD (Light Weight Deflectometer) & Benkelman Beam Deflectometer (BBD) on low volume roads to relate subgrade moduli using static &dynamic deflection methods using LWD & BBD. It was found that LWD provides reliable subgrade moduli values, & it can be used as a tool for quick subgrade strength evaluation.

It was found that most of the researchers have carried out nondestructive tests using LWD and Geogauge on pavement layers, but few have attempted to carry out this work on road shoulders. Therefore assessment of road shoulder condition is important in view of strength and safety. In this paper, an attempt has been made to correlate engineering properties with elastic modulus for road shoulder soil to obtain quick estimates of CBR and dry density values in the city of Patna, India.

The objectives of this study are (i) To assess the viability of using LWD & Geogauge devices to estimate the in-situ elastic modulus of constructed shoulders of roads, (ii) To evaluate the construction quality of shoulders and its compliance with the design standard by using on-site test techniques such as Geogauge and LWD, (iii) To carry out a comprehensive regression analysis on the various shoulder soil properties to develop best correlations between the elastic modulus and properties like dry density and CBR values.

II. TESTING PROGRAM

Field tests, as well as laboratory tests, were performed as stated in the sequence (i) Tests were conducted at 32 different locations in Patna city, India. The data of 25 locations were used to develop correlations and the remaining data of 7 locations were used to validate the correlations developed. (ii) First Geogauge was used to measure elastic modulus (E_G) of the compacted shoulder soil on all sites after preparing a leveled surface of the shoulder as stated in the Geogauge manualand then taking the average of three values taken at a site location. (iii) Then LWD was used to measure elastic modulus (E_{LWD}) of compacted shoulder soil as stated in LWD manual on the same points of as of Geogauge measured points by taking the average of the last three values of the six-reading taken at a site location. (iv) Bulk density of site location was determined at every site using sand replacement method according to **IS: 2720 – Part 28 (1974)** [12]. (v)The water content of the soil was determined by oven drying method according to IS**: 2720 – Part 2 (1973)** [13] to determine dry density. (vi)Dry density was determined using bulk density and water content using(8).

$$\text{Dry density}(\rho_d) = \frac{\text{Bulk Density}(\rho_b)}{1+\text{Water Content}(w)} \quad (8)$$

(vii) CBR values (unsoaked& soaked both) of site shoulders were determined in the laboratory according to guidelines mentioned in **IS: 2720-Part 16-1979** [14] by simulating the field conditions in the mold. (viii) Sieve analysis was performed as per **IS: 1498-1970** [15] to determine soil type. (ix) The same process was repeated at every site location to collect all data. (x) Analysis of the data collected was performed and results were obtained for developing correlations.

A. *CBR test*

The CBR test specimen in the mold was prepared by following the process as performed by **George et al.** [1]**.** The soil was excavated from each location whose CBR was to be calculated. The soil was then taken to the laboratory, covered inside a plastic bag so as to prevent the loss of moisture. The CBR tests were then performed in the laboratory by replicating the field conditions. For a known volume of the standard CBR mold, the weight of the soil needed to fill the mold for the field density obtained is computed. The CBR mold was filled with the soil in three layers of equal thickness with each layer filled with one-third of the total weight necessary to fill the mold. The soil was then compacted in each layer to the required thickness. The CBR tests were then conducted according to IS: 2720 – Part 16 (1979) [14]. This alternative approach was undertaken to determine the field CBR {unsoaked CBR (CBR_{US})} due to the unavailability of instruments for performing in-situ CBR tests. The same process was adopted to find the soaked CBR (CBR_S) with the difference that after compaction the mold is soaked in water for four days before performing the CBR tests.

III. THEORY

A. *Geogauge*

The Geogauge equipment was initially built by the defense industry to detect landmines. It gauges the in-situ stiffness of compacted soil at a rate of approximately 1 test per 1.5 minutes. It weighs approximately 10 kg (22 lbs), is 28 cm (11 inches) in diameter and 254mm (10 inches) tall, & rests on the surface of soil via a ring-shaped foot (Fig. 1). It has an annular ring that contacts the soil surface with an outside diameter of 11.4 cm (4.50 inch), an inside diameter of 8.9 cm (3.50 inch), and a thickness of 1.3 cm (0.50inch).

The operational principle of the Geogauge is to produce a very minute dynamic force of about 9 Newton at frequencies of 100 to 196 Hertz [3]. The operation of Geogauge involves causing a very minute displacement to the soil, less than 1.27 x 10^{-6} m (0.0005 inches) estimated by velocity sensors, at 25 steady state frequencies between 100 and 196 Hertz. The stiffness H_{SG} is calculated at each & every frequency by a microprocessor and the mean is displayed. The Geogauge elastic modulus can be obtained by converting the Geogauge stiffness utilizing the equation as given in(9) [5].

$$E_G = H_{SG}\frac{(1-\mu^2)}{1.77R} \qquad (9)$$

where E_G is the elastic modulus in MPa, H_{SG} is Geogauge stiffness reading in MN/m, μ is the Poisson's ratio, & R is the radius of the Geogauge foot (5.715 cm). In this work, the Poisson's ratio was chosen as 0.35 for the dense sandy soil to compute the Geogauge elastic modulus for the tested surface **(Nazzal)** [3].

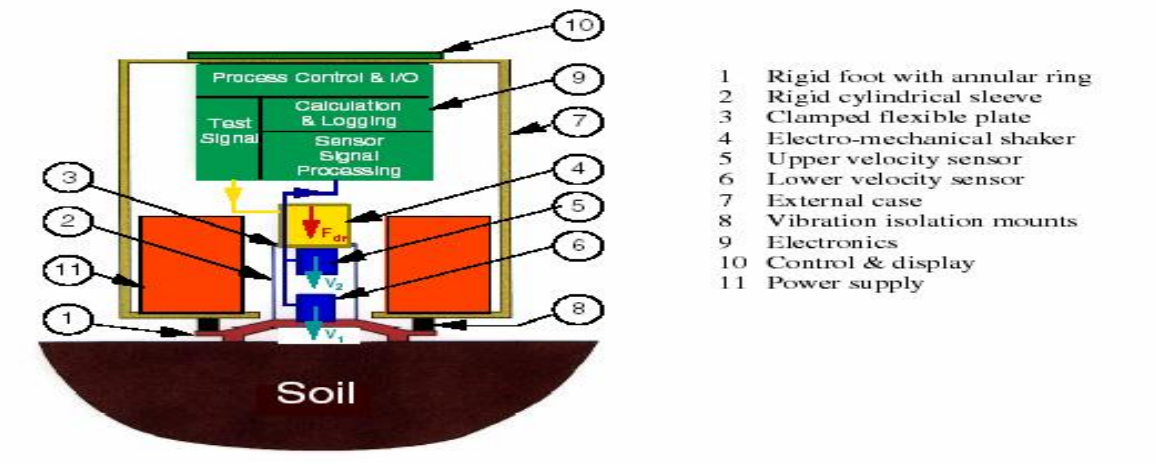

Fig. 1 - The Schematic of Geogauge [3]

B. *Light Weight Deflectometer (LWD)*

Light Weight Deflectometer (LWD) is a transportable falling weight deflectometer that was evolved as a substitute on-site testing device to the plate load test enabling rapid measurements without disturbing the soil. The 3031 LWD was used in this study (Fig. 2). It weighs 22 kg (49 lbs) and has a 10 kg (22 lbs) falling weight which impacts a rubber pad to create a load pulse of 15->30 milliseconds. For operating LWD safely, the drop weight is provided with a transportation-lock pin & guide rod with stabilizer. It has a load range of >15 kN. It measures both force and deflection, utilizing a velocity transducer (geophone) with a deflection range of 0-2200 μm [16].

The standard model has 1 geophone sensor but models with 3 geophones are also available that could give a simple deflection bowl. The measured center deflection is utilized to obtain the dynamic elastic modulus using the Boussinesq solution as shown in(10) [2].

$$E_{LWD} = \frac{K(1-\mu^2)\sigma \times R}{\delta_c} \qquad (10)$$

where E_{LWD} is LWD dynamic elastic modulus, K = Plate rigidity factor (generally assumed to be 2 for a flexible plate and π/2 for a rigid plate), $\boldsymbol{\delta}_c$ = Center deflection, σ = Applied Stress, R = Radius of the plate, μ = Poisson's ratio of soil.

In this work, the Poisson's ratio was chosen as 0.35 for the dense sandy soil [3], plate rigidity factor as 2 for a flexible plate and the diameter of the loading plate utilized was 300 mm to compute LWD elastic modulus for the tested soil.

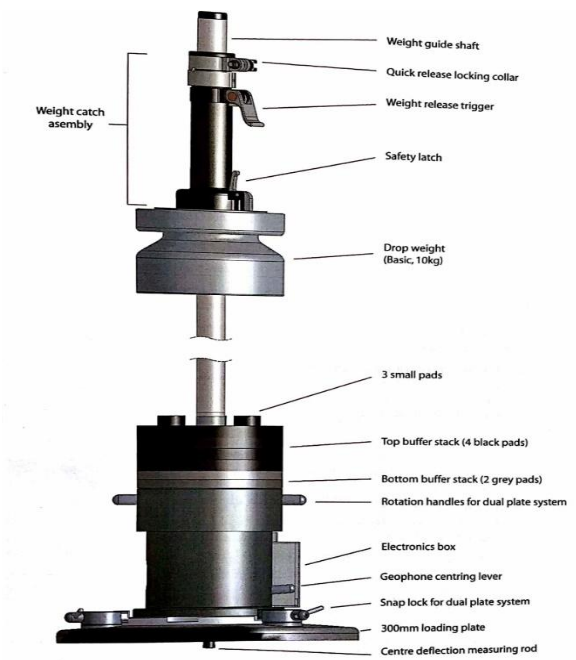

Fig. 2 - Light Weight Deflectometer [16]

IV. RESULTS AND DISCUSSION

The fields, as well as laboratory investigations of soil shoulder, are shown in Tables I and II along with descriptive statistics. These data were used for the development of correlations and its validation.

Overall 32 data points were selected out of which 78% data were used for the development of correlations and 22% data were used for the validation of developed correlations. The developed models were validated by comparing observed values to predicted values of soil properties like dry density, unsoaked CBR and soaked CBR by using statistical parameters such as coefficient of determination (R^2), average relative error, p-values, and standard error.

Table I: Observations comprising 78% data for development of correlations

Site	Global Coordinates	E_{LWD} (MPa)	S.D	E_G (MPa)	S.D	Bulk Density (ρ_b)(g/cm^3)	Water content (w) (%)	Dry Density (ρ_d)(g/cm^3)	CBR_{US} (%)	CBR_S (%)	% passing 75µ sieve
1	25° 37' 14.3472" N,85° 10' 21.8244" E	166.00	1.53	154.00	2.08	1.89	5.88	1.78	20.11	4.91	16.40
2	25° 37' 14.682" N,85° 10' 22.1232" E	163.00	2.00	147.00	1.53	1.85	6.65	1.73	16.08	3.50	20.40
3	25° 37' 15.0276" N,85° 10' 22.188" E	108.00	0.58	93.00	2.00	1.57	28.57	1.22	9.20	2.17	14.60
4	25° 37' 15.4056" N,85° 10' 22.2996" E	78.00	0.58	81.00	2.52	1.64	18.75	1.38	5.80	1.50	25.80
5	25° 37' 13.0584" N,85° 10' 19.0416" E	36.00	1.73	42.00	2.65	1.32	20.00	1.10	3.20	0.93	20.50
6	25° 37' 12.8136" N,85° 10' 19.0164" E	167.00	2.08	143.00	2.08	1.82	8.00	1.68	16.50	3.42	19.40
7	25° 37' 12.4644" N,85° 10' 18.9552" E	168.00	0.58	157.00	2.00	2.01	15.50	1.74	22.18	4.74	13.40
8	25° 37' 12.1692" N,85° 10' 18.9012" E	165.00	1.00	149.00	2.08	1.89	6.81	1.77	20.87	4.53	13.90
9	25° 37' 11.8776" N,85° 10' 18.9192" E	187.00	0.00	176.00	3.21	1.92	5.54	1.82	30.05	6.01	12.40
10	25° 37' 11.604" N,85° 10' 18.8796" E	88.00	0.58	80.00	2.52	1.38	12.34	1.23	6.34	1.58	19.60
11	25° 37' 11.3016" N,85° 10' 18.7788" E	69.00	0.00	79.00	2.31	1.44	20.37	1.20	3.03	0.87	24.80
12	25° 37' 10.9956" N,85° 10' 18.804" E	83.00	1.73	80.00	1.53	1.32	10.73	1.19	7.85	2.07	16.50
13	25° 37' 10.6392" N,85° 10' 18.7752" E	120.00	0.58	102.00	1.53	1.56	6.06	1.47	9.70	2.43	21.30
14	25° 37' 10.344" N,85° 10' 18.7428" E	47.00	0.58	44.00	3.06	1.31	10.51	1.18	6.77	1.89	18.40
15	25° 37' 9.6816" N,85° 10' 18.6744" E	110.00	0.00	103.00	2.52	1.43	11.87	1.28	9.56	2.47	16.70
16	25° 37' 9.336" N,85° 10' 18.6528" E	111.00	0.58	122.00	3.06	1.51	11.23	1.51	11.82	2.75	19.90
17	25° 37' 9.1272" N,85° 10' 18.6672" E	104.00	0.00	99.00	3.21	1.72	8.55	1.59	16.23	3.54	15.80
18	25° 37' 8.8104" N,85° 10' 18.6024" E	62.00	1.53	57.00	1.53	1.61	12.13	1.43	10.12	1.92	17.80
19	25° 37' 8.5332" N,85° 10' 18.5592" E	57.00	1.00	58.00	1.53	1.48	6.21	1.42	6.36	1.61	24.10
20	25° 37' 8.22" N,85° 10' 18.2352" E	61.00	0.58	49.00	2.08	1.47	17.63	1.25	8.20	2.01	17.80
21	25° 37' 8.5476" N,85° 10' 18.2424" E	68.00	1.53	59.00	2.65	1.50	16.85	1.29	5.57	1.35	22.50
22	25° 37' 8.8032" N,85° 10' 18.246" E	72.00	1.00	79.00	2.00	1.64	18.75	1.38	5.80	1.50	25.40
23	25° 37' 9.2928" N,85° 10' 18.2928" E	102.00	1.73	90.00	3.06	1.75	11.74	1.57	12.30	3.15	20.70
24	25° 37' 9.624" N,85° 10' 18.372" E	153.00	2.08	148.00	1.00	1.83	10.58	1.66	10.73	2.84	27.10
25	25° 37' 10.7328" N,85° 10' 18.4764" E	147.00	0.58	133.00	1.53	2.05	13.61	1.81	19.55	4.77	17.90
Min		36.00	0.00	42.00	1.00	1.31	5.54	1.10	3.03	0.87	12.40
Max		187.00	2.08	176.00	3.21	2.05	28.57	1.82	30.05	6.01	27.10
Avg		107.68	0.97	100.96	2.21	1.64	12.59	1.47	11.76	2.74	19.32
S.D		45.13	0.69	40.24	0.62	0.22	5.77	0.23	6.79	1.38	4.03

S.D-Standard Deviation

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Table II: Observations comprising 22% data for validation of correlations developed

Site	Global Coordinates	E_{LWD} (MPa)	S.D	E_G (MPa)	S.D	Bulk Density (ρ_b)(g/cm^3)	Water content (w) (%)	Dry Density (ρ_d)(g/cm^3)	CBR_{US} (%)	CBR_S (%)	% passing 75µ sieve
1	25° 37' 11.5716" N,85° 10' 18.5412" E	132.00	0.58	142.00	2.00	1.88	13.13	1.66	13.4	3.50	13.90
2	25° 37' 11.7444" N,85° 10' 18.552" E	92.00	0.00	95.00	2.08	1.51	5.71	1.43	7.31	2.08	22.80
3	25° 37' 12.1044" N,85° 10' 18.6168" E	72.00	1.53	70.00	3.21	1.52	14.85	1.32	6.18	1.69	22.10
4	25° 37' 12.504" N,85° 10' 18.6888" E	118.00	1.00	110.00	2.52	1.64	11.13	1.48	11.51	2.66	19.30
5	25° 37' 12.8676" N,85° 10' 18.7068" E	86.00	0.58	77.00	2.31	1.42	12.13	1.27	6.73	1.60	19.10
6	25° 37' 8.31" N,85° 10' 18.7464" E	69.00	1.53	67.00	1.53	1.26	8.09	1.17	6.62	1.70	17.50
7	25° 37' 8.5332" N,85° 10' 19.3548" E	77.00	1.00	83.00	1.53	1.35	9.10	1.23	6.58	1.99	19.00
Min		69.00	0.00	67.00	1.53	1.26	5.71	1.17	6.18	1.60	13.90
Max		132.00	1.53	142.0	3.21	1.88	14.85	1.66	18.51	3.50	22.80
Avg.		92.29	0.89	92.00	2.17	1.51	10.59	1.37	9.06	2.17	19.10
S.D		24.03	0.55	26.61	0.59	0.20	3.15	0.17	4.55	0.69	2.95

S.D-StandardDeviation

The soil classification based on grain size was done using sieve analysis as per Indian standard soil classification system **IS 1498-1970** [15]. It was observed that the soil particles passing 75µ sieve is less than 50% and the coarse fraction passing 4.75 mm sieve is more than 50%. Thus, the results show the soil to be coarse-grained, sandy to be specific.

The dry density and CBR of a compacted soil depend largely upon the degree of compaction, water content, and type of soil. The elastic modulus obtained using Geogauge (E_G) lies between 42 MPa and 176 MPa with an average value and standard deviation (SD) equal to 100.96 and 40.24 respectively. Whereas, unsoaked CBR values lie between 3.03% and 30.05%, with an average value and SD equal to 11.76% and 6.79 respectively. The correlation between unsoaked CBR and elastic modulus obtained using Geogauge is a polynomial relation of order two as shown in(11) and Fig. 3 which appears to be the most fitting correlation with an R^2 value of 0.798 and p-value less than 0.05. The value of unsoaked CBR increases with an increase in E_G non-linearly. For validation, it also facilitates the comparison of observed and predicted values of unsoaked CBR having an average relative error of 14.93% and linear regression line fit with an R^2 value of 0.875 as shown in Fig. 4, an estimated Standard error (SE) of 1.02, p-value less than 0.05 and Chi-square value of 2.56 which is less than the critical value at degree of freedom 6 and level of significance 5%. This indicates that the model developed is significant. The equation 11 is valid for a practical value of E_G ($E_G \neq 0$ and $35 < E_G < 190$ MPa).

$$(CBR)_{US} = 0.001(E_G)^2 - 0.124E_G + 9.342 \quad (R^2 = 0.798) \quad (11)$$

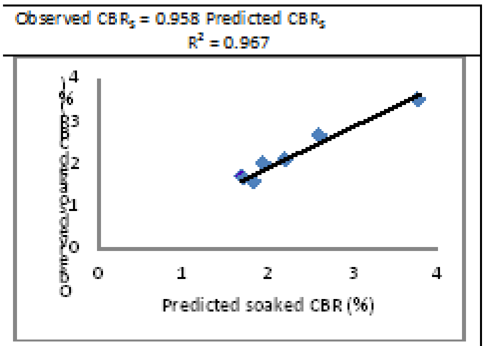

Fig.6 - Comparison between observed and predicted soaked CBR

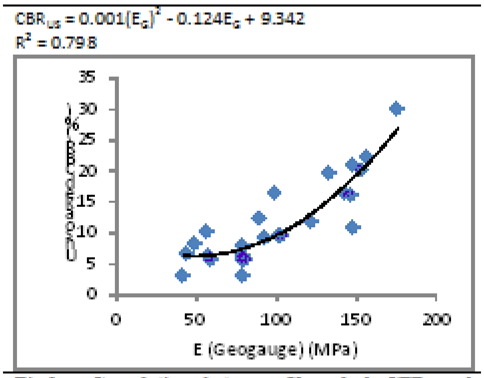

Fig.3 - Correlation between Unsoaked CBR and Geogaugeelastic Modulus (E_G)

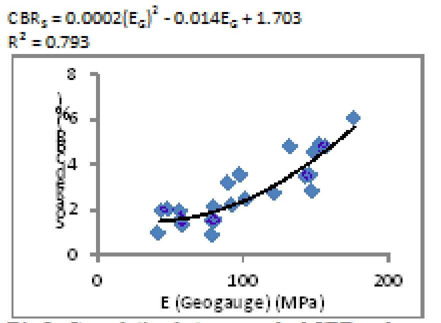

Fig.5 - Correlation between soaked CBR and Geogauge elastic Modulus (E_G)

The soaked CBR values lie between 0.87% and 6.01%, with an average value and SD equal to 2.74% and 1.38 respectively. The correlation between soaked CBR and elastic modulus obtained using Geogauge is a polynomial relation of order two as shown in(12) and Fig. 5 which appears to be the most fitting correlation with an R^2 value of 0.793 and p-value less than 0.05. The value of soaked CBR increases with an increase in E_G non-linearly. For validation, it also facilitates the comparison of observed and predicted values of soaked CBR having an average relative error of 5.13% and linear regression line fit with an R^2 value of 0.967 as shown in Fig. 6, an estimated Standard error (SE) of 0.124 & p-value less than 0.05. This indicates that the model developed is significant. The equation 12 is valid for a practical value of E_G ($E_G \neq 0$ and $35 < E_G < 190$ MPa).

$$(CBR)_S = 0.0002(E_G)^2 - 0.014E_G + 1.703 \quad (R^2 = 0.793) \qquad (12)$$

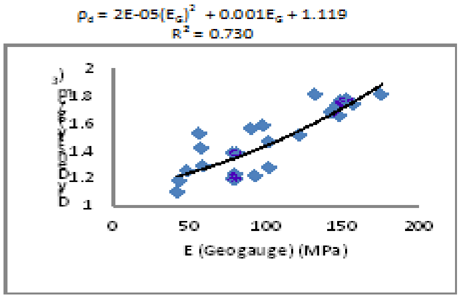

Fig.7 - Correlation between Dry Density and Geogauge elastic modulus (E_G)

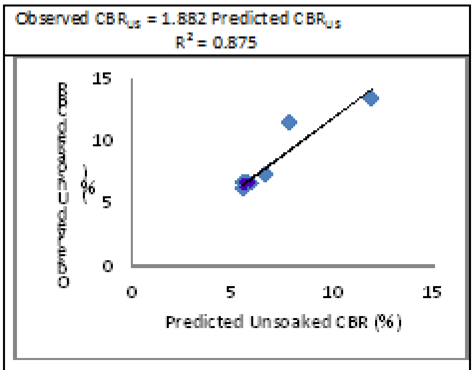

Fig.4 - Comparison between observed and predicted unsoaked CBR

Dry density values lie between 1.1 g/cm^3 and 1.82 g/cm^3, with an average value and SD equal to 1.47g/cm^3 and 0.23 respectively. The correlation between dry density and elastic modulus obtained using Geogauge is a polynomial relation of order two as shown in(13) and Fig. 7 which appears to be the most fitting correlation with an R^2 value of 0.730 and p-value less than 0.05. The value of dry density increases with an increase in E_G non-linearly. For validation, it also facilitates the comparison of observed and predicted values of dry density having an average relative error of 3.9% and linear regression line fit with an R^2 value of 0.864 as shown in Fig. 8, an estimated Standard error (SE) of 0.063 & p-value less than 0.05. This indicates that the model developed is significant. The equation 13 is valid for a practical value of E_G ($E_G \neq 0$ and $35 < E_G < 190$ MPa).

$$\rho_d = 2E-05(E_G)^2 + 0.001E_G + 1.119 \quad (R^2 = 0.730) \qquad (13)$$

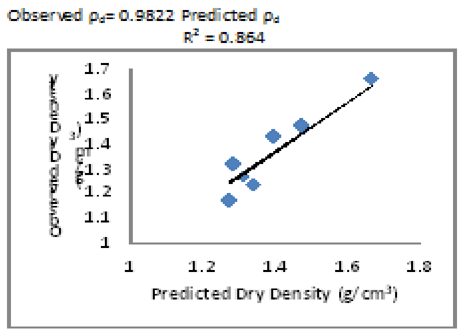

Fig.8 - Comparison between observed and predicted dry density

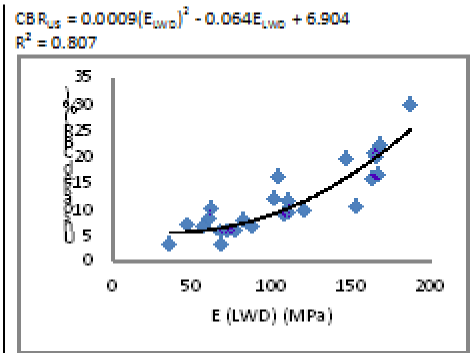

Fig.9 - Correlation between Unsoaked CBR and LWD elastic Modulus

The elastic modulus obtained by LWD lies between 36 MPa and 187 MPa with an average value and standard deviation (SD) equal to 107.68 and 45.13 respectively. The correlation between unsoaked CBR and elastic modulus obtained using LWD is a polynomial relation of order two as shown in(14) and Fig. 9 which appears to be the most fitting correlation with an R^2 value of 0.807 and p-value less than 0.05. The value of unsoaked CBR increases with an increase in E_{LWD} non-linearly. For validation, it also facilitates the comparison of observed and predicted values of unsoaked CBR having an average relative error of 10.62% and linear regression line fit with an R^2 value of 0.968 as shown in Fig. 10, an estimated Standard error (SE) of 0.513, p-value less

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than 0.05 and Chi-square value of 0.66 which is less than the critical value at degree of freedom 6 and level of significance 5%. This indicates that the model developed is significant. The equation 14 is valid for a practical value of E_{LWD} ($E_{LWD}\neq 0$ and $35<E_{LWD}<190$ MPa).

$$(CBR)_{US} = 0.0009(E_{LWD})^2 - 0.064E_{LWD} + 6.904 \quad (R^2 = 0.807) \tag{14}$$

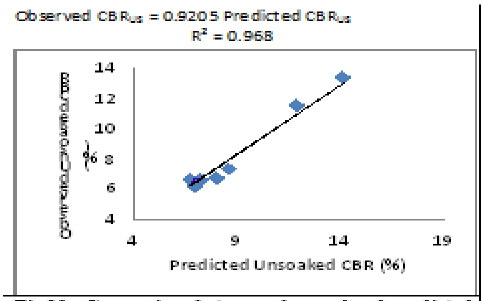

Fig.10 - Comparison between observed and predicted unsoaked CBR

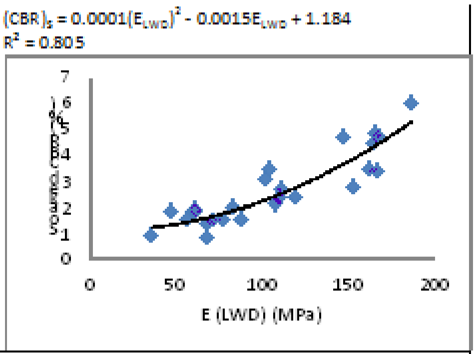

Fig.11 - Correlation between Soaked CBR and LWD elastic Modulus (E_{LWD})

The correlation between soaked CBR and elastic modulus obtained using LWD is a polynomial relation of order two as shown in(15) and Fig. 11 which appears to be the most fitting correlation with an R^2 value of 0.805 and p-value less than 0.05. The value of soaked CBR increases with an increase in E_{LWD} non-linearly. For validation, it also facilitates the comparison of observed and predicted values of soaked CBR having an average relative error of 11.92% and linear regression line fit with an R^2 value of 0.862 as shown in Fig. 12, an estimated Standard error (SE) of 0.256 & p-value less than 0.05. This indicates that the model developed is significant. The equation 15 is valid for a practical value of E_{LWD} ($E_{LWD}\neq 0$ and $35<E_{LWD}<190$ MPa).

$$(CBR)_S = 0.0001(E_{LWD})^2 - 0.0015E_{LWD} + 1.184 \quad (R^2 = 0.805) \tag{15}$$

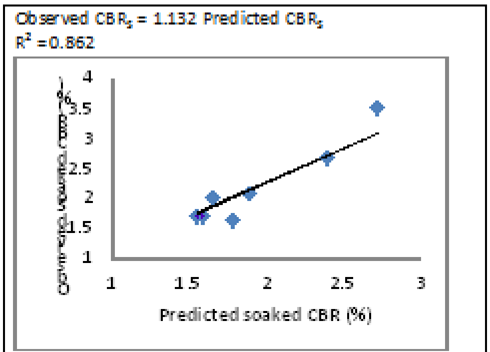

Fig.12 - Comparison between observed and predicted soaked CBR

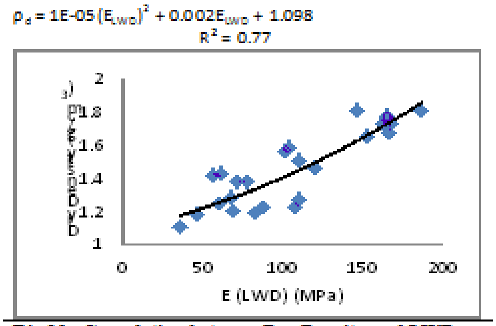

Fig.13 - Correlation between Dry Density and LWD elastic modulus (E_{LWD})

The correlation between dry density and elastic modulus obtained using LWD is a polynomial relation of order two as shown in(16) and Fig. 13 which appears to be the most fitting correlation with an R^2 value of 0.770 and p-value less than 0.05. The value of dry density increases with an increase in E_{LWD} non-linearly. For validation, it also facilitates the comparison of observed and predicted values of dry density having an average relative error of 5.24% and linear regression line fit with an R^2 value of 0.733 as shown in Fig.14, an estimated Standard error (SE) of 0.088 & p-value less than 0.05. This indicates that the model developed is significant. The equation 16 is valid for a practical value of E_{LWD} ($E_{LWD}\neq 0$ and $35<E_{LWD}<190$ MPa).

$$\rho_d = 1E-05(E_{LWD})^2 + 0.002E_{LWD} + 1.098 \quad (R^2 = 0.770) \tag{16}$$

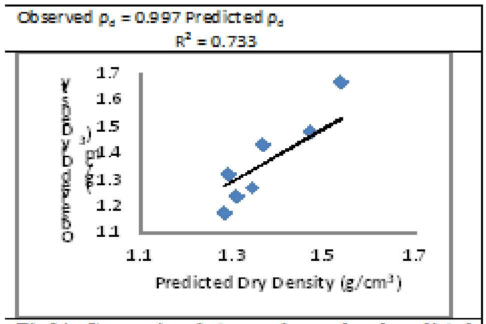

Fig.14 - Comparison between observed and predicted dry density

Researchers have developed correlations with linear, logarithmic linear and polynomial variations. This may be due to available data and local conditions.

A. *Exploring the influence of Geotechnical Parameters on Elastic Modulus obtained using Geogauge and LWD*

The equation 17, having an R^2 value of 0.970 and a p-value less than 0.05, developed as part of this study points out that the values of dry density and unsoaked CBR show a positive influence whereas water content shows a negative effect on the elastic modulus obtained using Geogauge. For validation, it also facilitates the comparison of observed and predicted values of E_G having an average relative error of 9.1%, a linear regression line fit with an R^2 value of 0.955, an estimated Standard error (SE) of 9.51 and a p-value less than 0.05.

$$E_G = 41.93\,\rho_d + 3.6\,(CBR)_{US} - 0.185\,w \quad (R^2 = 0.970) \tag{17}$$

The equation 18, having an R^2 value of 0.971 and a p-value less than 0.05, developed as part of this study points out that the values of dry density and soaked CBR shows a positive influence whereas water content shows a negative effect on the elastic modulus obtained using Geogauge. For validation, it also facilitates the comparison of observed and predicted values of E_G having an average relative error of 7.75%, a linear regression line fit with an R^2 value of 0.980, an estimated Standard error (SE) of 7.68 and a p-value less than 0.05.

$$E_G = 34.86\,\rho_d + 19.01\,(CBR)_S - 0.14\,w \qquad (R^2 = 0.971) \tag{18}$$

The equation 19, having an R^2 value of 0.9705 and a p-value less than 0.05, developed as part of this study points out that the values of dry density and unsoaked CBR shows a positive influence whereas water content shows a negative effect on the elastic modulus obtained using LWD. For validation, it also facilitates the comparison of observed and predicted values of E_{LWD} having an average relative error of 6.15%, a linear regression line fit with an R^2 value of 0.899, an estimated Standard error (SE) of 6.2 and a p-value less than 0.05.

$$E_{LWD} = 41.7\,\rho_d + 4.3\,(CBR)_{US} - 0.28\,w \qquad (R^2 = 0.9705) \tag{19}$$

The equation 20, having an R^2 value of 0.972 and a p-value less than 0.05, developed as part of this study points out that the values of dry density and soaked CBR shows a positive influence whereas water content shows a negative effect on the elastic modulus obtained using LWD. For validation, it also facilitates the comparison of observed and predicted values of E_{LWD} having an average relative error of 7.38%, a linear regression line fit with an R^2 value of 0.900, an estimated Standard error (SE) of 7.86 and a p-value less than 0.05.

$$E_{LWD} = 33.245\,\rho_d + 22.72\,(CBR)_S - 0.22\,w \qquad (R^2 = 0.972) \tag{20}$$

V. CONCLUSIONS

An investigation was carried out at 32 locations and found the soil to be coarse-grained (sandy). The models were developed using 78% data, and for validation, 22% of data were used. Non-destructive tests were evaluated using Geogauge and LWD. Dry density was evaluated in-situ while water content and CBR tests were performed in the laboratory.

The modulus values obtained using Geogauge and LWD ranged between 35 MPa and 190 MPa. The result of unsoaked CBR from 3% to 35%, soaked CBR from 0.8% to 7%, dry density from 1 g/cm^3 to 2 g/cm^3, and water content from 5% to 30%.

Correlations were developed between elastic modulus obtained by NDT devices under consideration and destructive test engineering properties. The result of regression analysis gives non-linear relationships and shows good correlation based on statistical testing. All regression models have an R^2 value greater than 0.7 and a p-value less than 0.05.

The models were validated through statistical testing and found a significant correlation between observed and predicted values of various parameters. The validation of various correlations developed shows an average relative error of less than 15 %, an R^2 value greater than 0.7 and a p-value less than 0.05.

The outcome of this work proposes that Geogauge and LWD can be consistently utilized to envisage the dry density and CBR values and thus can be utilized to estimate the strength or stiffness parameters of shoulders.

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