OPEN ACCESS

Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) |ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article

Development and Testing of California Bearing Ratio Machine for Evaluating the Strength of Materials for Use in Roads and Pavements

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DOI: https://doi.org/10.36348/sjet.2026.v11i02.001 | **Received:** 03.12.2025 | **Accepted:** 29.01.2026 | **Published:** 03.02.2026

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Abstract

An electrically-operated California Bearing Ratio (CBR) machine was designed, fabricated with locally-sourced materials, calibrated and tested with the aim of providing high precision machine obtainable at lower cost. Materials were selected based on the ability to withstand mechanical loads, stiffness and dimensional stability, wear resistance, corrosion resistance, machinability and cost-effectiveness. The major component parts were designed using standard equations. For material components such as the loading frame, CBR moulds and reaction rings, mild steel was used, hardened medium carbon steel was used for the plunger, while high-grade spring steel was used for the load-measuring components for high elastic recovery. Calibration result gave proving ring constant as 0.02 kN/div. CBR test results on soil samples under unsoaked conditions gave CBR values ranging from 4.85 – 6.91 %, indicating poor to fair soils requiring stabilization or treatment for subgrade material. For soil tested under soaked conditions, the lowest CBR value of 0.82% showed poor subgrade soil that requires substantial stabilization, while the sample with the highest CBR value of 3.15% requires significant improvement. Statistical analysis of data using Minitab software version 2018 applied Fisher Pairwise tests for differences of means at 95% level of significance, which showed that soaked 2.5mm and unsoaked 5mm samples with P = 0.007 and soaked 5mm and unsoaked 5mm with P = 0.14 are significantly different for the top, and soaked 2.5mm and unsoaked 5mm having P = 0.028, are significantly different for the bottom. CBR values for all other top and bottom samples are not significantly different.

Keywords: CBR Design, Calibration, Roads and Pavements, Bearing capacity, Load-penetration graph, Minitab.

1.0 INTRODUCTION

The California Bearing Ratio (CBR) test has played a crucial role in road construction since it was first developed by the California Division of Highways in the late 1920s. At a time when vehicle traffic was steadily increasing, engineers needed a reliable method to design roads that could withstand the growing load. The CBR test was developed to measure the strength of subgrade soils, providing essential data for designing flexible pavements that are both durable and safe. Over the years, the test was standardized to ensure consistent results across different projects, and it was soon adopted by other organizations, including the U.S. Corps of Engineers, particularly for the design of airfield pavements. As road construction technology evolved, so did the CBR test. The testing equipment and procedures have been refined to improve accuracy and reliability, accounting for factors such as load, gear configuration, tyre pressure, repetitions, and environmental conditions. Today, the CBR test remains one of the most widely used methods for evaluating subgrade strength, forming the backbone of pavement design in many parts of the world (Khatti *et al.,* 2018; Kasa & Wubineh, 2023; Liu *et al.,* 2023).

The results of the CBR test are invaluable for road engineers. They guide decisions on the type and thickness of pavement required for a specific project, ensuring long-term stability and durability. The test also helps assess the quality of construction materials, such as base course aggregates, and their suitability for road construction. Because soils differ in type and strength, the test can be carried out both in laboratories and in the field, providing flexible and practical insights for engineers (Arora, 2004; Rehman *et al.,* 2015; Ali *et al.,* 2021; BS 1377-2, 2022). The relationship between CBR values and pavement thickness is empirical, and engineers rely on design charts developed from years of experience to determine appropriate construction specifications (Sutton, 1979).

Several factors influence the long-term CBR beneath a pavement, including soil type, water table depth, efficiency of drainage systems, protection offered by the pavement, and moisture content during construction (Barnes, 2000). In laboratory settings, the test involves preparing a soil sample in a cylindrical steel mould and pressing a steel plunger of 50 mm diameter into the sample at a controlled rate, while measuring the force required for penetration (Sutton, 1979; Smith & Smith, 1990; Kasa & Wubineh, 2023). Despite its simplicity, the test provides essential information that engineers around the world rely on to design flexible pavements.

Over the years, researchers have studied the CBR test to better understand its relationship with soil properties. Black (1962) explored connections between CBR, soil plasticity, and suction in British soils, while Semen (2006) examined numerous CBR tests in the United States to develop reliable prediction methods for different site conditions. McGough (2010) analyzed data from hundreds of tests in Australia and South Africa, establishing useful correlations between CBR and soil characteristics, such as grading and plasticity. Similar studies in India have investigated how soil plasticity affects CBR values for local soils (Ramasubbarao & Sankar, 2013; Yadav *et al.,* 2014). In simple terms, the California Bearing Ratio is the percentage ratio of the force required to penetrate a soil sample with a standard 50 mm plunger at a set rate to the force needed to achieve the same penetration in a standard material. This straightforward measurement provides a practical and reliable way to assess how soils will perform under traffic loads.

The aim of this research is to fabricate a high-precision CBR testing machine using locally available materials, making it significantly more affordable. This machine will serve as a valuable tool for teaching and research, while also creating opportunities for revenue generation, bridging the gap between practical engineering training and real-world application.

2.0 MATERIALS AND METHODS

2.1 Materials

Material selection for the California Bearing Ratio (CBR) machine was based on the ability to withstand mechanical loads, stiffness and dimensional stability, wear resistance, corrosion resistance, machinability, as well as cost-effectiveness and availability. The major components of the CBR machine are cross bar, load columns, load ring, dial gauge, displacement hanger, spacer disc, surcharge loads (annular and circular), CBR moulds, penetration piston, base plate, advance shaft, reducer gear box, belt, electric motor, housing, control panel and the skeleton (or frame structure).

Mild steel was used for material components such as the loading frame, CBR moulds and reaction rings which must resist deformation and failure under load, and for good weldability without compromising strength. Hardened medium carbon steel was used for the plunger, while high-grade spring steel were used for the load-measuring components such as load ring and proving ring due to low creep and high elastic recovery, since they must maintain calibration under repeated use. However, in material selection, a balance was considered between performance and cost. Materials were selected based on economic factors without sacrificing performance.

2.2 Methods

CBR Machine Design Equations and Design Calculations

The design equations and design calculations for the major component parts of the California Bearing Ratio (CBR) testing machine are presented as follows:

Design Criteria and Assumptions

Cross bar: 50 × 50 × 400 mm (mild steel), Load columns: Ø30 mm SST × 1200 mm long (threaded ends), Load ring: Design (max) vertical test load for F_{design} = 50 kN, Dial gauge: 0–10 mm (0.002 mm resolution), Spacer discs (annular & circular): Ø150 × 16 mm with Ø50 mm hole (steel), CBR mould: Ø150 mm (ID) with base & collar, Penetration piston: Ø50 mm × 100 mm SST, Base plate: Ø200 mm × 20 mm MS, Advance shaft (power screw): Ø50 mm SST threaded × 300 mm, Reducer gearbox: output speed 1.25 mm/min, Belt: T-belt, 4 mm pitch, Motor: single-phase 1.0 HP (≈ 746 W), 1400 rpm, Mild Steel properties: E = 210,000 MPa, ν = 0.30, density, $\rho_{steel} = 7\,850$ kg/m^3.

Design Equations and Design Calculations
Design of Crossbar

$$Second\ Moment\ of\ Area, I = \frac{b^4}{12} \quad (1)$$

$$Maximum\ Moment, M_{max} = P_{max} \times \frac{L}{4} \quad (2)$$

$$Bending\ Stress,\ \sigma_{max} = M_{max} \times \frac{(b/2)}{I} \quad (3)$$

To determine the design Calculation consider; (b = 50 mm, L = 400 mm, P = 50 kN)

From equation (1) $Second\ Moment\ of\ Area, I = \frac{b^4}{12} = \frac{50^4}{12} = 520833.33 mm^4$

From equation (2) $Maximum\ Moment,\ M_{max} = P_{max} \times \frac{L}{4} = \frac{50{,}000 \times 400}{4} = 5 \times 10^6\ N.mm$

From equation (3) will give

$Bending\ Stress,\ \sigma_{max} = M_{max} \times \frac{(b/2)}{I} = \frac{5 \times 10^6 \times (50/2)}{520833.33} = 240\ N/mm^2$, or 240 MPa.

Design for Load Columns (30 mm dia × 1200 mm)

$$A = \frac{\pi * d^2}{4} \quad (4)$$

$$A = \frac{\pi * d^2}{4} = \pi * \frac{30^2}{4} = 706.8583\ mm^2$$

$$Moment\ of\ Inertia, I = \frac{\pi * d^4}{64} \quad (5)$$

$$Moment\ of\ Inertia, I = \frac{\pi * d^4}{64} = \pi * \frac{30^4}{64} = 39760.7820\ mm^4$$

$$Euler\ Buckling\ load,\ P_{\{cr\}} = \frac{\pi^2 * E * I}{(K * L)^2} \quad (6)$$

$$P_{\{cr\}} = \pi^2 * 210000 * \frac{39760.7820}{1 * 1200^2} = 57228.38\ N \approx 57.23\ kN$$

Design for Load Ring (50 kN capacity)

$$Axial\ Stress,\ \sigma = \frac{P}{A_{\{ring\}}} \quad (7)$$

$$\sigma = \frac{50000}{1000} = 50 \frac{N}{mm^2} (50\ MPa)$$

$$Bearing\ Stress,\ q = \frac{P}{A_{\{contact\}}} \qquad (Das, 2010) \quad (8)$$

$$A_{\{contact\}} = \frac{\pi * d^2}{4} \quad (9)$$

$$A_{\{contact\}} = \frac{\pi * d^2}{4} = \frac{\pi * 50^2}{4} = 1963.5\ mm^2$$

Therefore $q = \frac{50{,}000}{1963.5} = 25.46\ mm^2$

Design for Dial Gauge (Proving Ring Conversion, 0 – 10 mm, 0.002 resolution)

$$Proving\ Ring\ Force,\ F_r = k_r * \Delta \quad (10)$$

$K_r = 20000\ N/mm,\quad \Delta = 0.5mm,\ R = 1$

Therefore $F_r = 20000 * 0.5 = 10000\ N$

$$Specimen\ Load,\ P_{\{specimen\}} = F_r * R \quad (11)$$

Hence; $Specimen\ Load,\ P_{\{specimen\}} = F_r * R = 10000 * 1 = 10000\ N$

$Force\ Resolution,\quad \Delta F = k_r * dial\ resolution)$

$\Delta F = 20000 * 0.002 = 40\ N/mm$

Design for Displacement Hanger

$$Revolutions\ Required,\ N_{[rev]} = \frac{x}{L_s} \quad (12)$$

Equation (12) gives; $Revolutions\ Required,\ N_{[rev]} = \frac{x}{L_s} = \frac{2.5}{5} = 0.5\ rev$

Design for Spacer Disc and Surcharge (150 mm OD, 50 mm hole, 16mm thick)

$$Annular\ Area,\ A_{\{annulus\}} = \left(\frac{\pi}{4}\right) * (D_o^2 - D_i^2), \quad (13)$$

$$A_{\{annulus\}} = \left(\frac{\pi}{4}\right) * (150^2 - 50^2) = 15707.9633\ mm^2$$

$$Surcharge\ Pressure,\ q_s = \frac{(W_s * g)}{A_m} \qquad (\text{Bhatia}, 2014) \quad (14)$$

$$q_s = \frac{(2.0 * 9.81)}{\left(\frac{\pi}{4}\right) * 150^2} = 1109.8857\ N/m^2 = 1.1099\ kPa\ \ (for\ a\ 2.0\ kg\ disc)$$

Design for CBR Mould (150 mm dia)

$$Cross - Sectional\ Area\ of\ mould,\ A_m = \frac{\pi * D_m^2}{4}, \quad (15)$$

$$A_m = \pi * \frac{150^2}{4} = 17671.4587\ mm^2$$

Design for Penetration Piston (50 mm dia × 100 mm)

Parameters: *Axial force, P = 10000 N; Diameter, d = 50 mm; Length, L = 100 mm (0.10 m); Modulus of elasticity, E = 200 GPa (or 2 x 10^{11} Pa); Effective length, K = 1(for pinned-pinned).*

Cross-sectional Area of piston,

$$A_p = \frac{\pi * d_p^2}{4} \quad (16)$$

$$A_p = \pi * \frac{50^2}{4} = 1963.5\ mm^2$$

$$Axial\ Stress,\ \sigma_a = \frac{P}{A_p} \quad (17)$$

$$\sigma_a = \frac{10000}{1963.5} = 5.09\ N/mm^2$$

Design for Base Plate (200 mm dia × 20 mm thick)

$$Cross - sectional\ area,\ A_b = \frac{\pi * D_b^2}{4} \quad (18)$$

$$A_b = \pi * \frac{200^2}{4} = 31415.9265\ mm^2$$

$$Average\ Bearing\ Stress,\ q_b = \frac{P}{A_b} \quad (Gere\ and\ Goodno, 2012) \quad (19)$$

$$q_b = \frac{50000}{31415.9265} = 1.59154943\ N/mm^2 = 1.59\ MPa$$

Design for Advance Shaft (50 mm dia threaded × 300 mm)

$$Torque\ Requirement\ (power\ screw),\ T = \frac{(P * L_s)}{(2 * \pi * \eta_s)} \quad (20)$$

$$T = \frac{(50000 * 5)}{(2 * \pi * 0.3)} = 132629.1192\ N \cdot mm = 132.63\ N \cdot m$$

Design for Reducer Gear Box (speed = 1.25mm/min)

Data: v = 1.25 mm/min, L_s = 5 mm/rev

$$Output\ Shaft\ RPM,$$

$$n_s = \frac{v}{L_s}\left(\frac{rev}{min}\right) \quad (21)$$

$$n_s = \frac{1.25}{5} = 0.25\ rev/min$$

Design for Belt Drive (T-belt, 4 mm pitch)

$$Belt\ Speed,\ v_b = \frac{(2 * \pi * r * n)}{60} \quad (Budynas\ \&\ Nisbett, 2015) \quad (22)$$

Data: *r = 0.05m, n = 1400 rpm, Tension on tight side, T_1 = 1000 N, Tension on slack side, T_2 = 500 N*

$$v_b = \frac{(2 * \pi * 0.05 * 1400)}{60} = 7.33\ m/s$$

$$Power\ Transmission,\ P = (T1 - T2) * v_b \quad (23)$$

$$P = (1000 - 500) * 7.33 = 3665\ N.m/s\ or\ 3.665\ kW$$

Design for Electric Motor

Parameters: *1 HP ≈ 746 W, Motor speed, n = 1400 rpm*

$$Angular\ Speed,\ \omega = \frac{(2 * \pi * n)}{60} \quad (24)$$

$$Angular\ Speed,\ \omega = \frac{(2 * \pi * n)}{60} = 2 * \pi * \frac{1400}{60} = 146.61\ rad/s$$

$$Motor\ Torque,\ T_m = \frac{P}{\omega} \quad (25)$$

$$Motor\ Torque, \quad T_m = \frac{P}{\omega} = \frac{746}{146.61} = 5.09\ N \cdot m$$

Design for Housing (2 mm thick MS Plate)

$$Critical\ Buckling\ Stress, \quad \sigma_{\{cr\}}$$

$$\sigma_{\{cr\}} = \frac{(k * \pi^2 * E)}{(12 * (1 - \nu^2))} * \left(\frac{t}{b}\right)^2 \quad (26)$$

$$\sigma_{\{cr\}} = 4 * \pi^2 * \frac{210000}{(12 * (1 - 0.3^2))} * \left(\frac{2}{200}\right)^2 = 75.92\ N/mm^2 \approx 75.92\ MPa$$

Design for Control Panel

$$Motor\ Current\ (approx),\ I_{\{FL\}} = \frac{P}{(V * \eta * pf)} \quad (27)$$

$$I_{\{FL\}} = \frac{746}{(230 * 0.9 * 0.85)} = 4.239840864\ A \approx 4.24\ A$$

Design for Skeleton (Frame Members)

Parameters: $A = 1000\ mm^2$, $P = 50\ kN, M = 50 \times 10^6, c = b/2 = 50/2$

Fromm equation (1)$Second\ Moment\ of\ Area, I = \frac{b^4}{12} = \frac{50^4}{12} = 520833.33\ mm^4$

$$Axial\ (normal)\ Stress, \sigma_a = \frac{P}{A} \quad (28)$$

$$Axial\ (normal)\ Stress, \sigma_a = \frac{P}{A} = \frac{50000}{1000} = 50\ N/mm^2\ (or\ 50\ MPa)$$

$$Bending\ Stress,\ \sigma_b = \frac{(M * c)}{I} \quad (Khurmi\ and\ Gupta, 2005) \quad (29)$$

$$\sigma_b = \frac{50 \times 10^6 \times 25}{520833.33} = 240\ N/mm^2$$

$$Combined\ Stress,\ \sigma = \sigma_a + \sigma_b \quad (30)$$

$$\sigma = 50 + 240 = 290\ N/mm^2$$

Bolt Shear Stress,

Bolt shear stress, $\tau = \frac{P}{A_{shear}}$ (31)

For M16 bolts, d = 16mm, Shear Force, P = 10000 N

Considering equation (16); $A_{shear} = \frac{\pi * d^2}{4} = \frac{\pi * 16^2}{4} = 201.06\ mm^2$

$$\tau = \frac{10000}{201.06} = 49.75\ MPa$$

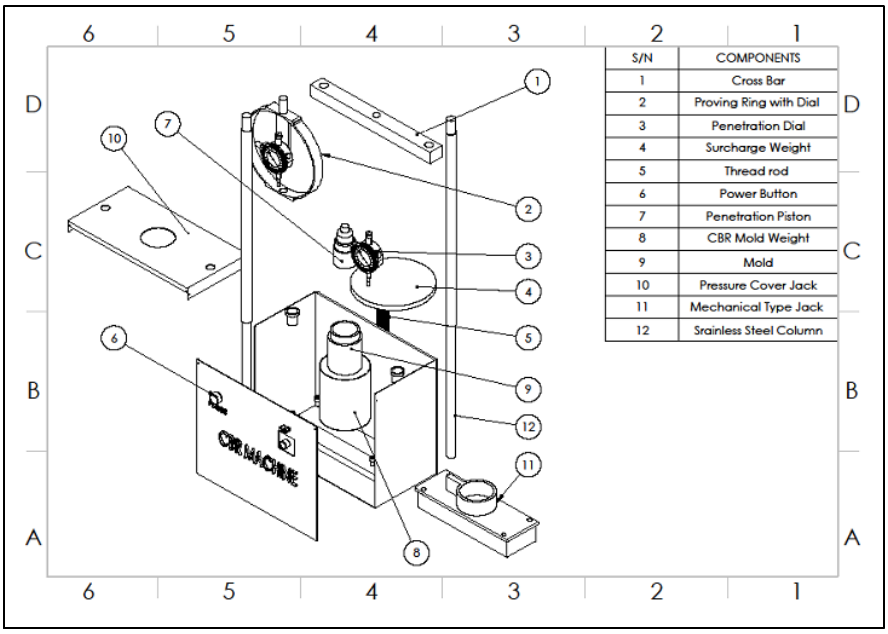

Figure 1: Exploded View of the CBR Machine

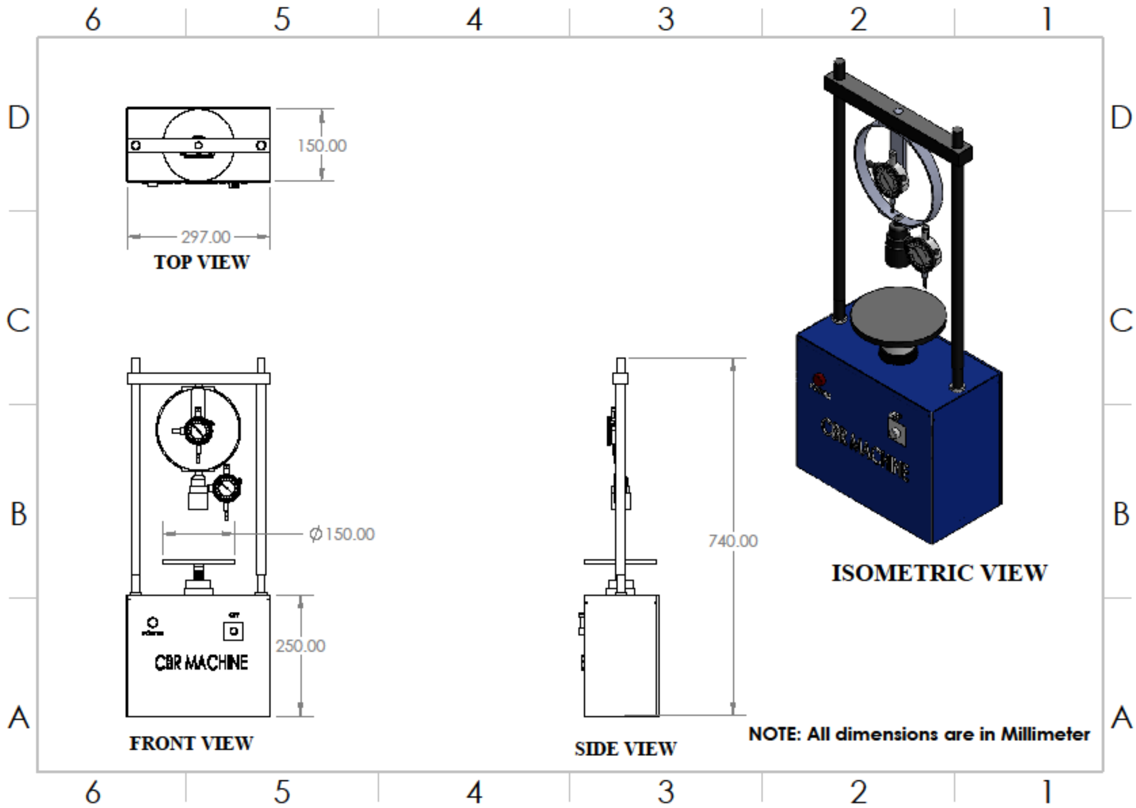

Figure 2: Orthographic projection and Isometric view of the CBR machine

Fabrication and calibration Process
The fabrication and calibration processes are illustrated in plates 1 to 5

Plate 1: Pictorial view of the completed CBR machine

Plate 2: CBR Mould

Plate 3: CBR Annular Surcharge Weight

Plate 4: Spacer Disc (150 mm)

Plate 5: Weighing of Mould with Sample

3.0 Calibration of Proving Ring of the CBR Machine

Calibration is the normal process of determining the correction factor and accuracy of the proving ring used to measure load in a CBR testing setup. Calibration ensures that the proving ring gives correct load readings corresponding to its deformation (deflection).

Calibration is significant because it ensures the accuracy and reliability of measurements, instruments and test results. According to International Standards Organization (ISO), calibration ensures that measurements are accurate and reliable; it enables the comparison of measurements between different instruments, laboratories or locations; it is essential for quality control and assurance (ISO/IEC Guide, 2014).

3.1 Calibration Procedure

The first step in the procedure for calibration involves: Cleaning the proving, mounting it in the calibration frame in a vertical position, attaching the dial gauge on the proving ring to measure deflection, and ensuring the setup is properly aligned so the load is applied axially through the center of the ring. Then, the dial gauge is set to zero before loading, and load is applied in gradual increments. For each increment, record of load applied and the corresponding deflection on the proving ring dial gauge are taken until maximum capacity is reached. Unloading is done at the same rate as loading, and the corresponding deflection readings are taken and checked for elastic recovery. Finally, the calibration graph was plotted, as Figure 3, and the calibration factor is calculated as the ratio of the applied load to the dial reading, and expressed in units of force per division (kN/division).

Table 1: Calibration Result

Load (kg)	Force (kN)	Proving Ring Deflection (Division)	Force/Division
10	0.01	0.5	0.02
20	0.02	1.0	0.02
30	0.03	1.5	0.02
40	0.04	2.0	0.02
50	0.05	2.5	0.02
60	0.06	3.0	0.02
70	0.07	3.5	0.02
80	0.08	4.0	0.02
90	0.09	4.5	0.02
100	0.10	5.0	0.02
		$\Sigma \frac{F/Div}{N}$	**0.20/10**

1 kg = 0.00981kN ≈ 0.01kN

Therefore, the Calibration Factor (C.F.) = 0.02kN/Div

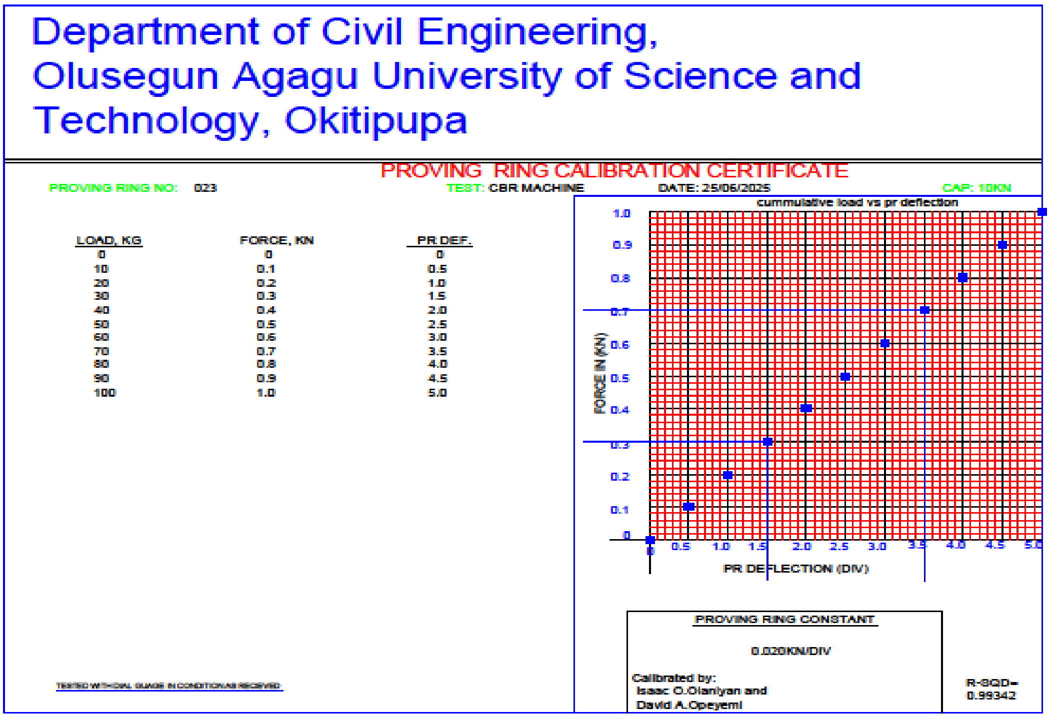

Figure 3: Calibration Graph for CBR Machine

4.0 CBR Test Results on Soil Sample

The newly developed apparatus was used to carry out CBR tests on soil samples PS-01, PS-02 and PS-03 taken within the University campus as unsoaked samples, while the soaked equivalents were obtained and tested after being soaked for 4 days. The results are presented in Figures 4 to 9 for each sample, and is followed by calculation of CBR values respectively by using equation 32.

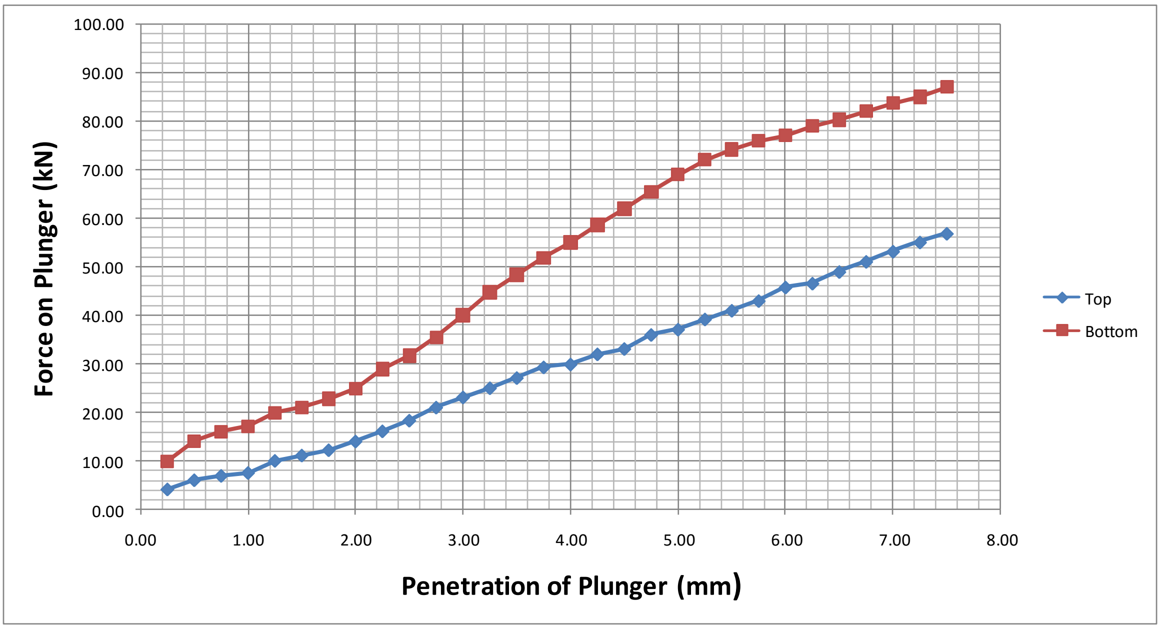

Figure 4: Load – Penetration Graph for Soil Sample PS-01

Calculation of CBR Value for Sample PS-01 (Figure 4)

The calibrating factor of the CBR machine is determined to be 0.020 kN/Div.
Therefore, the CBR value for the sample tested is computed as follows:

$$CBR\ Value = \frac{Test\ Load\ (Gauge\ Reading\ \times\ Calibrating\ factor)kN}{Standard\ Load\ (13.24\ kN\ or\ 19.96\ kN)} \times 100 \qquad (32)$$

For Sample PS-01, the bearing values areas follows:

Penetration (mm)	2.5	5.0
Top	2.76%	3.72%
Bottom	4.79%	6.91%

Therefore, the CBR value for Sample PS-01 = 6.91%.

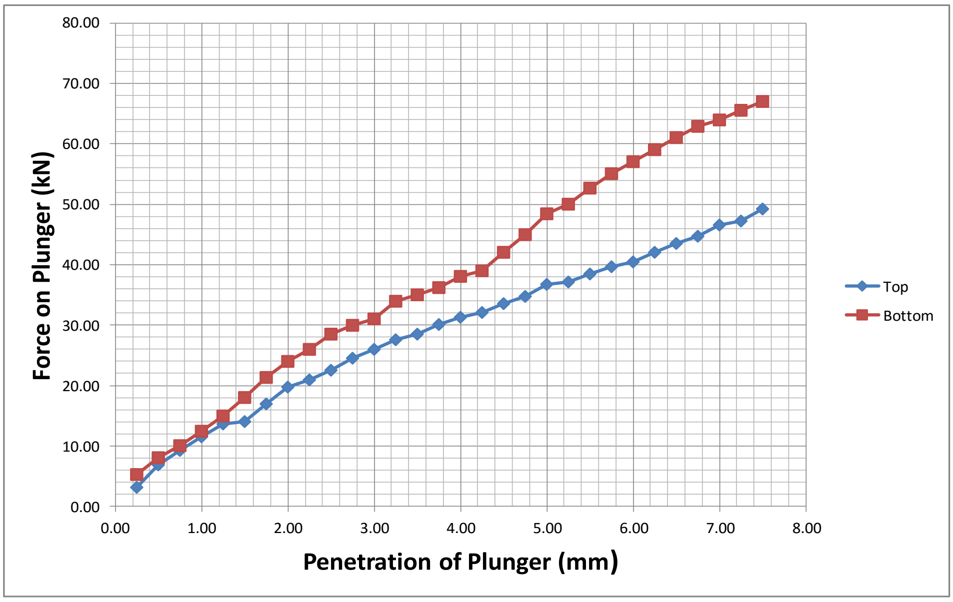

Figure 5: Load – Penetration Graph for Soil Sample PS-02

Calculation of CBR Value for Sample PS-02 (Figure 5)
For Sample PS-02, the bearing values areas follows:

Penetration (mm)	2.5	5.0
Top	3.40 %	3.68 %
Bottom	4.31 %	4.85 %

Therefore, the CBR value for Sample PS-02 = 4.85 %

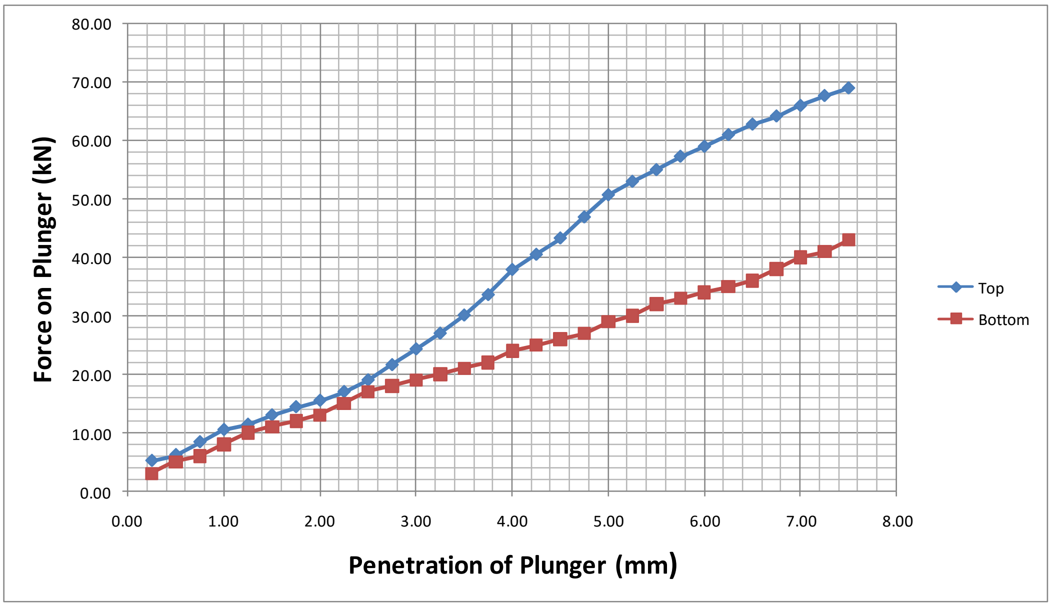

Figure 6: Load – Penetration Graph for Soil Sample PS-03

Calculation of CBR Value for Sample PS-03 (Figure 6)
For Sample PS-03, the bearing values are as follows:

Penetration (mm)	2.5	5.0
Top	2.87 %	5.08 %
Bottom	2.57 %	2.91 %

Therefore, the CBR value for Sample PS-03 = 5.08 %

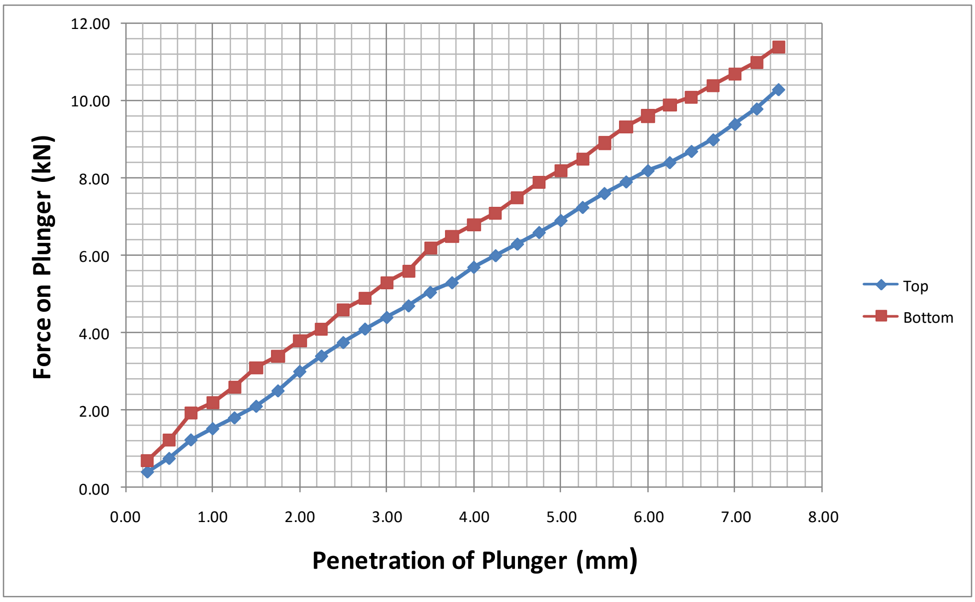

Figure 7: Load – Penetration Graph for Soil Sample PS-01S (Soaked)

Calculation of CBR Value for Sample PS-01S (Figure 7)
For Sample PS-01S, the bearing values areas follows:

Penetration (mm)	2.5	5.0
Top	0.57 %	0.69 %
Bottom	0.69 %	0.82 %

Therefore, the CBR value for Sample PS-01S = 0.82 %

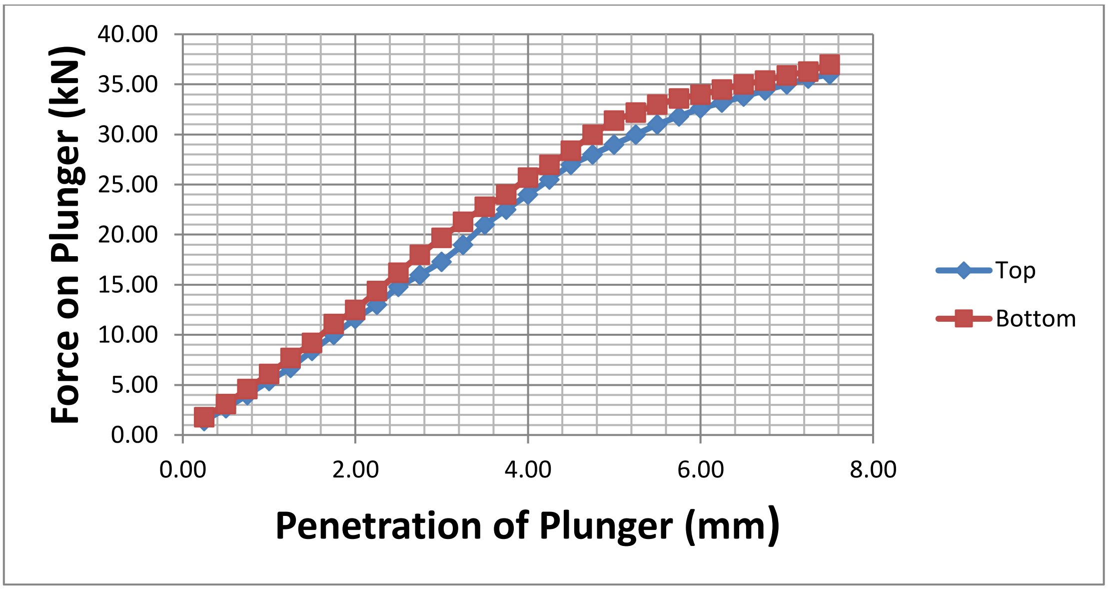

Figure 8: Load – Penetration Graph for Soil Sample PS-02S (Soaked)

Calculation of CBR Value for Sample PS-02S (Figure 8)
For Sample PS-02S, the bearing values areas follows:

Penetration (mm)	2.5	5.0
Top	2.24 %	2.91 %
Bottom	2.45 %	3.15 %

Therefore, the CBR value for Sample PS-02S = 3.15 %

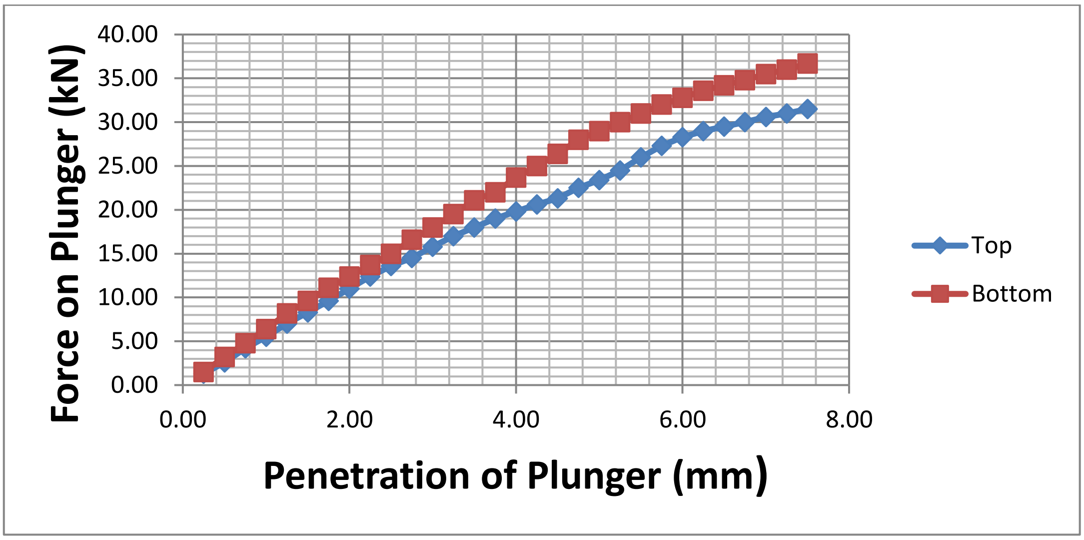

Figure 9: Load – Penetration Graph for Soil Sample PS-03S (Soaked)

Calculation of CBR Value for Sample PS-03S (Figure 9)
For Sample PS-03S, the bearing values areas follows:

Penetration (mm)	2.5	5.0
Top	2.05 %	2.34 %
Bottom	2.27 %	2.91 %

Therefore, the CBR value for Sample PS-03S = 2.91 %

5.0 DISCUSSION OF CBR TEST RESULTS

5.1 Classification of CBR Values

The California Bearing Ratio (CBR) values are commonly used to categorize soils for roads and pavements. The range of CBR values for soaked and unsoaked conditions can be broadly classified in Table 2 as follows (AASHTO 1993; BS 1377: Part 4; NHBC, 2023; ASTM, 2025; LHDG, 2025):

Table 2: Range of CBR Values and Soil classification

CBR Values	Classification for Use as Subgrade Soil
CBR values (< 3%)	Very poor subgrade soils, often requiring significant stabilization
CBR values (3-5%)	Poor subgrade soils, may require stabilization or treatment
CBR values (5-10%)	Fair subgrade soils, can be used as subgrade with some stabilization
CBR values (10-20%)	Good subgrade soils, suitable for subgrade with minimal stabilization
CBR values (> 20%)	Excellent subgrade soils, can be used as subgrade or base course
Soaked CBR values (< 2%)	Very poor subgrade soils
Soaked CBR values (2-5%)	Poor to fair subgrade soils
Soaked CBR values (> 5%)	Good subgrade soils

5.2 Discussion of Results for Unsoaked Samples

The CBR test results for the three soil samples under unsoaked conditions are discussed as follows:

- **Sample PS-01**: CBR value of 6.91%, indicating a fair to good subgrade soil suitable for low to moderate traffic roads (Figure 4).
- **Sample PS-02**: CBR value of 4.85%, indicating a poor subgrade soil that may require stabilization or treatment before use (Figure 5).
- **Sample PS-03**: CBR value of 5.08%, indicating a fair subgrade soil that can be used with some stabilization (Figure 6).

It can be inferred that the CBR values of the three samples vary, with PS-01 showing the highest value (6.91%) and PS-02 showing the lowest value (4.85%). This suggests that the soil samples have different engineering properties, which may be due to variations in soil composition, moisture content, or compaction characteristics.

Implications for Road Construction

Based on the CBR values, the following implications can be drawn:

- **Sample PS-01:** Can be used as a subgrade material with minimal stabilization, suitable for low to moderate traffic roads.
- **Sample PS-02:** May require significant stabilization or treatment to improve its strength and durability, potentially suitable for low-traffic roads or alternative uses.
- **Sample PS-03:** Can be used as a subgrade material with some stabilization, suitable for low-traffic roads or areas with moderate traffic.

Further investigation may, however, be necessary to determine the underlying causes of the variations in CBR values and to develop strategies for improving the engineering properties of the soil samples. This could include additional testing, such as gradation analysis, Atterberg limits, or compaction tests.

5.3 Discussion of Results for Soaked Samples

For soaked CBR values, the ranges are often lower due to reduced soil strength. The results for the soaked samples are discussed as follows:

- **Sample PS-01S**: CBR value of 0.82%, indicating a very poor subgrade soil that is likely to be unstable and require significant stabilization or replacement (Figure 7).
- **Sample PS-02S**: CBR value of 3.15%, indicating a poor subgrade soil that may require substantial stabilization or treatment before use (Figure 8).
- **Sample PS-03S**: CBR value of 2.91%, also indicating a poor subgrade soil that may require significant improvement or modification (Figure 9).

The inference that can be drawn from these results is that the soaked CBR values vary significantly among the samples, with PS-01S showing an extremely low value (0.82%) while PS-02S shows the highest value (3.15%). This suggests that the soils have different engineering properties and behaviors under soaked conditions.

Implications for Road Construction

Based on the soaked CBR values, the following implications can be drawn:

- **Sample PS-01S:** Would likely require complete replacement or significant stabilization with additives like cement or lime to improve its strength and durability.
- **Samples PS-02S and PS-03S:** Would require substantial stabilization or treatment to improve their strength and durability, and may be suitable for low-traffic roads or alternative uses with proper design and construction.

Further investigation may be necessary to determine the underlying causes of the low soaked CBR values and to develop strategies for improving the engineering properties of the soil samples. This could include additional testing, such as mineralogical analysis, to better understand their behaviour under different moisture conditions.

5.4 Statistical Analysis of Data

Table 3: Summary of California Bearing Ratio (CBR) Soil Test Results

		Bearing Value at:				**Bearing Value at:**	
Unsoaked Samples		**2.5 mm penetration**	**5.0 mm penetration**	**Soaked Samples**		**2.5 mm penetration**	**5.0 mm penetration**
PS 01	Top	2.76	3.72	PS 01S	Top	0.57	0.69
	Bottom	4.79	6.91		Bottom	0.69	0.82
PS 02	Top	3.40	3.68	PS 02S	Top	2.24	2.91
	Bottom	4.31	4.85		Bottom	2.45	3.15
PS 03	Top	2.87	5.08	PS 03S	Top	2.05	2.34
	Bottom	2.57	2.91		Bottom	2.27	2.91

Statistical analysis of data was carried out using the Minitab software version 2018. The software was used to carry out Fisher Pairwise comparison of CBR test results summarized into table 3 using Fisher LSD method at 95% level of significance. The results are presented as follows:

(i) For top samples

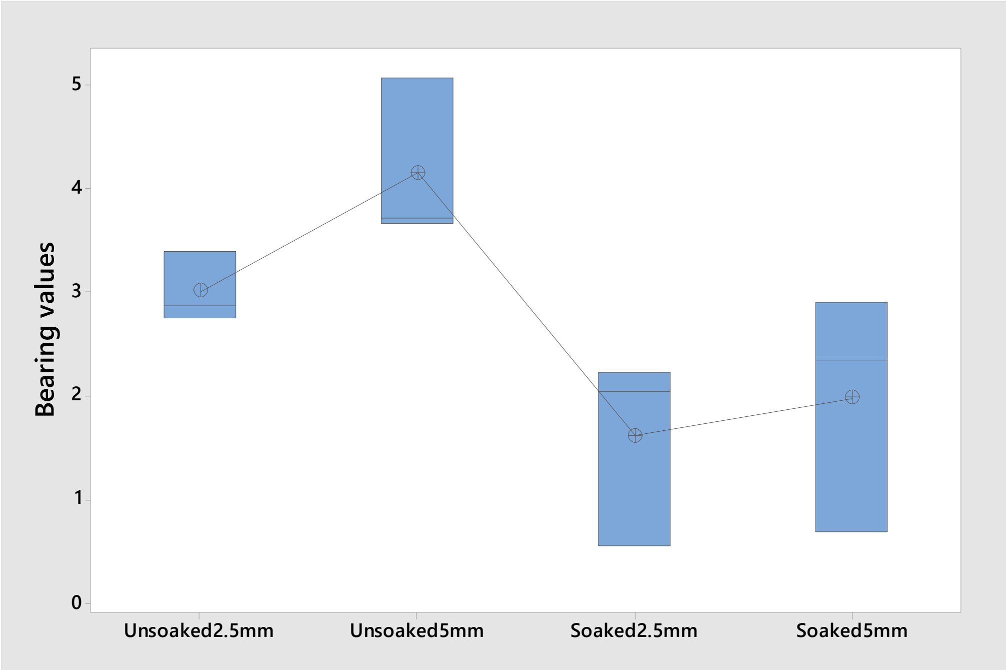

Fig. 10: Fisher Pairwise Comparison for top samples with bearing values

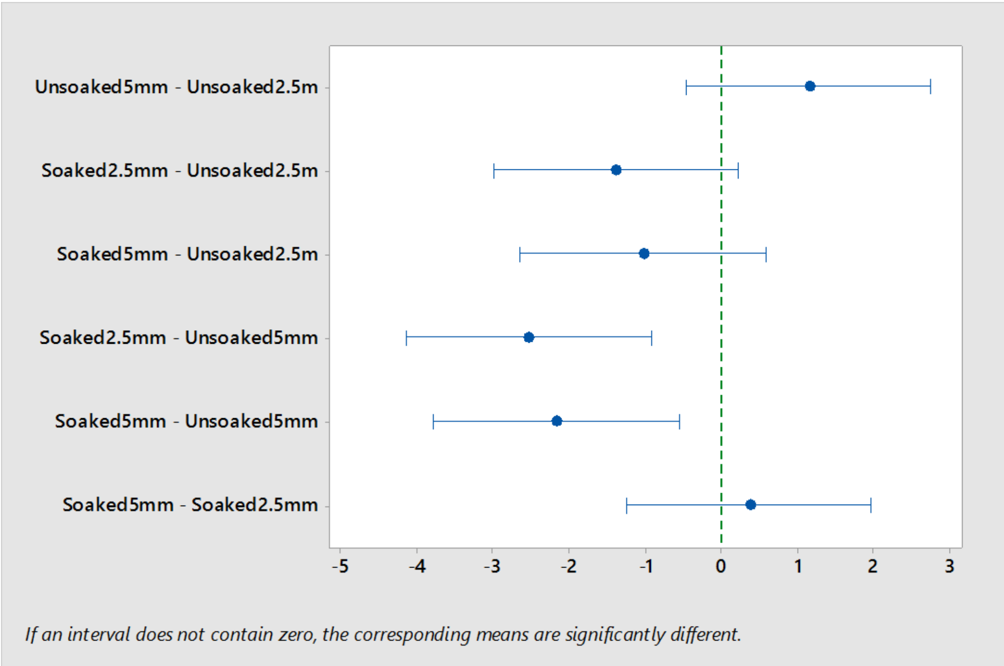

Fig. 11: Fisher Pairwise Comparison of soaked and unsoaked top samples

Figures 10 shows Fisher Pairwise Comparison for top samples with bearing values, while Figure 11 shows similar comparison for soaked and unsoaked top of mould samples.

Table 4: Grouping Information for Top Samples

Factor	N	Mean	Grouping	
Unsoaked 5mm	3	4.158	A	
Unsoaked 2.5mm	3	3.011	A	B
Soaked 5mm	3	1.981		B
Soaked 2.5mm	3	1.619		B

Table 4 shows grouping information for top samples using the Fisher LSD Method and 95% confidence level. Since the means that do not share a letter are significantly different, unsoaked 5mm sample is significantly different from soaked 5mm and soaked 2.5mm.

Table 5: Fisher Individual Tests for Differences of Means for Top Samples

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Unsoaked5mm - Unsoaked2.5m	1.147	0.697	(-0.460, 2.755)	1.65	0.138
Soaked2.5mm - Unsoaked2.5m	-1.392	0.697	(-3.000, 0.215)	-2.00	0.081
Soaked5mm - Unsoaked2.5m	-1.030	0.697	(-2.638, 0.578)	-1.48	0.178
Soaked2.5mm - Unsoaked5mm	-2.539	0.697	(-4.147, -0.932)	-3.64	0.007
Soaked5mm - Unsoaked5mm	-2.177	0.697	(-3.785, -0.570)	-3.12	0.014
Soaked5mm - Soaked2.5mm	0.362	0.697	(-1.246, 1.970)	0.52	0.618

At 95% level of significance, if $P < 0.05$, there is significant difference between the samples, and conversely if $P > 0.05$, there is no significant difference between the samples. In Table 5, soaked 2.5mm and unsoaked 5mm have P value of 0.007, showing that they are significantly different. Similarly, soaked 5mm and unsoaked 5mm have P value of 0.14, indicating that they are significantly different. Other samples are not significantly different in terms of CBR values.

(ii) For bottom samples:

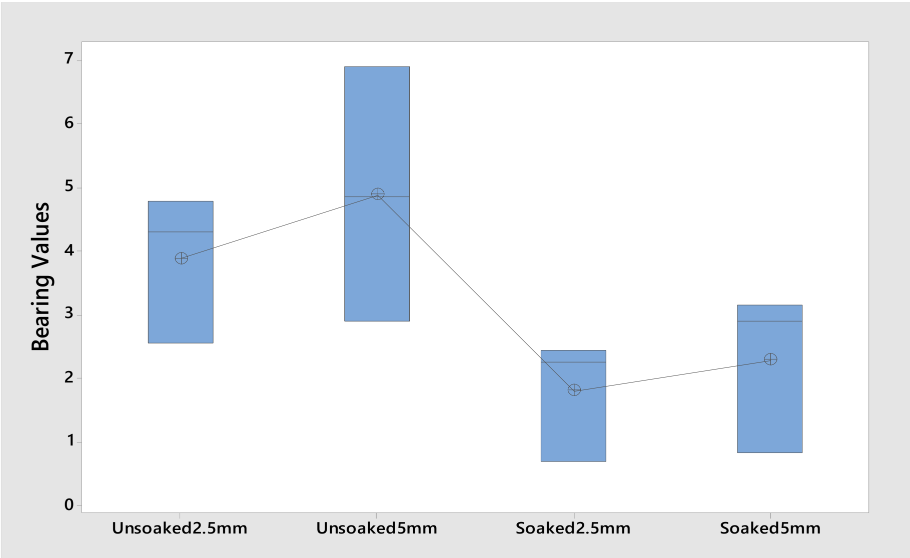

Fig. 12: Fisher Pairwise Comparison for bottom samples with bearing values

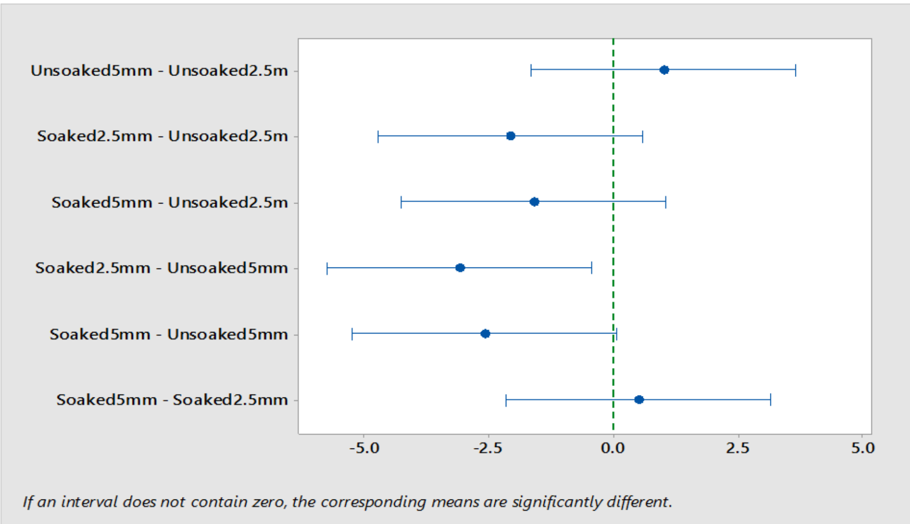

Fig. 13: Fisher Pairwise Comparison of soaked and unsoaked bottom samples

Figures 12 shows Fisher Pairwise Comparison for bottom samples with bearing values, and Figure 13 shows similar comparison for soaked and unsoaked bottom samples.

Table 6: Grouping Information for Bottom Samples

Factor	N	Mean	Grouping	
Unsoaked 5mm	3	4.89	A	
Unsoaked 2.5mm	3	3.887	A	B
Soaked 5mm	3	2.291	A	B
Soaked 2.5mm	3	1.803		B

Table 6 shows grouping information for bottom samples using the Fisher LSD Method and 95% confidence level. The means that do not share a letter are significantly different, indicating that unsoaked 5mm bottom sample is significantly different from soaked 2.5mm.

Table 7: Fisher Individual Tests for Differences of Means for Bottom samples

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
Unsoaked5mm - Unsoaked2.5m	1.00	1.15	(-1.65, 3.66)	0.87	0.409
Soaked2.5mm - Unsoaked2.5m	-2.08	1.15	(-4.74, 0.57)	-1.81	0.108
Soaked5mm - Unsoaked2.5m	-1.60	1.15	(-4.25, 1.06)	-1.39	0.203
Soaked2.5mm - Unsoaked5mm	-3.09	1.15	(-5.74, -0.43)	-2.68	0.028
Soaked5mm - Unsoaked5mm	-2.60	1.15	(-5.25, 0.05)	-2.26	0.054
Soaked5mm - Soaked2.5mm	0.49	1.15	(-2.16, 3.14)	0.42	0.682

In Table 7, at 95% level of significance, soaked 2.5mm and unsoaked 5mm have P value of 0.028, which means that they are significantly different. However, the tests for difference of means showed that the CBR values for all other bottom samples are not significantly different.

6.0 CONCLUSION

The primary objectives of this study was to design, fabricate and evaluate a new California Bearing Ratio (CBR) machine that could be used for evaluating the bearing capacity of the subgrade soil, which is essential for ensuring the long-term stability and durability of roads and pavements. Throughout the study, attempt was made to create an affordable, reliable, and locally accessible apparatus that could replace traditional, expensive testing equipment.

The new CBR apparatus was calibrated and tested, and the results obtained proved that the machine is not only effective in its performance, the apparatus provided consistent, repeatable, and reliable data, which aligns well with the expected performance based on the literature [7], [29]. Statistical analysis showed that at 95% level of significance, soaked 2.5mm and unsoaked 5mm top samples with P = 0.007 as well as soaked 5mm and unsoaked 5mm with P = 0.14 are significantly different, while other top samples are not significantly different in CBR values. Similarly, soaked 2.5mm and unsoaked 5mm for bottom samples have P = 0.028, suggesting that they are significantly different, whereas the CBR values for all other bottom samples are not significantly different.

The newly developed CBR apparatus has proven to be a cost-effective alternative to the expensive imported equipment, which makes it particularly beneficial for use in regions where access to high-cost, imported equipment is limited. The apparatus offers a feasible and affordable solution for local laboratories and testing centers looking to improve their testing capabilities without the need for significant capital investment.

Conflict of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Acknowledgment

This study was funded by the Tertiary Education Trust Fund under the 2024 Institution-Based Research funding programme.

Authorship principles

All authors whose names appear on the submission made substantial contributions to the design, fabrication and testing of the CBR machine, the correspondent author drafted the work, and it was jointly revised and approved for publication. The authors are both accountable for all aspects of the work done.

Data availability statements

The authors hereby states that any required data related to this work will be made available on request in order to promote the integrity, and replication of our research, thereby making it easier for the research community to build on and credit our work.

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