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Geoenvironmental use of $CaCo_3$ sludge in subgrade soil for a greener sugar industry

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The sugar refinery industry in Thailand produced million tons of sugar annually, generating an even larger amount of calcium carbonate sludge as a byproduct. This study examined the compaction enhancement and efficiency of subgrade material made of $CaCO_3$ sludge (10 to 30%), ordinary Portland cement, OPC (1 to 3%) and unqualified crushed rocks. A total of 12 specimens were tested by CBR ad electric resistivity measurements in addition to a reference specimen (100% unqualified crushed rock). The CBR test results showed that using OPC (with a limited dose) and CaCO3 sludge (up to 30%) in the mix designs could give an optimal balance in compaction enhancement (higher CBR value, lower dry density or smaller blow number) and reduction in cost and CaCO3 emission of the mixed material. For example, the samples ($SC_{1,2,3}$-10) with 10% CaCO3 sludge and 1%, 2–3% of OPC have the CBR value increased from 29 to 83, 113, and 146, respectively, or by comparing between the SC_0-0 unmixed sample with SC_0-10 (having 10% of CaCO3 sludge) it is observed a reduction in dry density from 2,189 to 2,109 gm/cc, while the CBR value remained the same at 29%. The SC_1-30 sample (1% OPC, 30% $CaCO_3$ sludge) gave the best balance of cost saving (15% in cost reduction), decarbonization (15% reduction in CO_2 emmision) and compaction enhancement (22% increase in CBR value) compared to the SC_0-0 sample of 100% unqualified crushed rock. The study highlighted the successful application of electrical resistivity measurements in testing and monitoring the quality of pavement mixed with $CaCO_3$ sludge. A strong correlation between CBR value and electrical resistivity was found, allowing a good prediction of the former from the latter. The findings of this research are expected to serve as a valuable reference for improving soil compaction efficiency, promoting zero-waste practices, and developing high-quality subgrades made from recycled materials like $CaCO_3$ sludge that can become a viable and cost-effective alternative of subgrade material in road construction practice.

Keywords Calcium carbonate sludge, Electrical resistivity, CBR values, Zero-waste

Soil compaction is a fundamental process in pavement construction, directly influencing structural stability, energy consumption, and overall project cost[1]. Traditional subgrade stabilization methods often rely on ordinary Portland cement (OPC) and crushed rocks, both of which contribute significantly to material expenses and environmental impact[2].

Cement-stabilized subgrade is a compacted, designed mixture of crushed in-situ soil, water, and moderate cement[1]. Soil stabilized subgrade has an enhanced load-bearing capacity and can support heavier loads without excessive settlement by using cement[2–5]calcium carbonate sludge[6]lime and limestone[7]calcium lignosulphonate[8] and solid waste[9]. Cement binds particles together, forming a durable mixture, while $CaCO_3$ sludge and lime reacts with clay minerals to reduce plasticity and increase load-bearing capacity. The solid waste is often used with lime or cement to enhance pozzolanic reactions and improving strength over time[10]. Dredged lakebed sediment-stabilised with ordinary Portland cement (OPC) and fly ash (FA) is also used for use as pavement materials in road infrastructure[11].

The use of $CaCO_3$ sludge as a soil stabilizer is increasingly recognized for its economic advantages and positive environmental impact. However, it differs from traditional stabilization methods such as lime, fly ash, and geopolymers. While $CaCO_3$ sludge is a sustainable and low-cost option, it has slower strength development compared to other methods. Lime is highly effective for clay soils but has environmental concerns. Fly ash is

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economical and enhances soil properties but requires activators. Geopolymers provide superior strength but are costly and less commonly used in large-scale soil stabilization projects[12]. A comparison of some materials that can be as used as replacement constituents in mixing subgrade material for road construction is presented in Table 1.

The environmental impact of different materials used for soil stabilization must be taken into account. The energy-intensive process of producing ordinary Portland cement (OPC) increases greenhouse gas emissions, primarily CO_2[13,14]. Calcinating (heating) limestone releases carbon dioxide during the lime production process[15,16]. The high cost of OPC and unqualified crushed rocks, coupled with the substantial carbon emissions by OPC production, make it imperative to explore an alternative, cost-effective, and sustainable stabilization materials.

Thailand has produced significantly more sugarcane in the past ten years. In the 1980s, the average national cane production was 30 million metric tons; in the 1990s, it rose to 50 million metric tons; and between 2010 and 2017, it averaged 100 million tons[17]. The continuously increasing number of operational sugar mills in Thailand over the past two decades is shown in Fig. 1a, while Fig. 1b illustrates Thailand's annual sugarcane area and production from 2010 to 2024. As shown in Fig. 1c, in 2024, Thailand's sugar production was projected to reach approximately 10.2 million metric tons (MMT), reflecting a 16% increase from the previous year[18]. Given that 3 to 5 tons of calcium carbonate ($CaCO_3$) sludge are typically generated per ton of sugar produced, this would result in an estimated 41 million tons of $CaCO_3$ sludge. Unlike OPC, $CaCO_3$ sludge has negligible production emissions (0 kg CO_2/ton) and is available at a significantly lower cost of 2.5 USD/m^3, making it an economically viable substitute.

Figure 2 and Eq. 1 illustrate how the carbonation system's fine syrup process generates $CaCO_3$ sludge as a byproduct[20]. The chemical reaction between lime or calcium hydroxide [$CaOH_2$] and carbon dioxide [CO_2] results in the formation of calcium carbonate [$CaCO_3$] as shown below:

$$C_a(OH)_2 + CO_2 \rightarrow C_aCO_3 + H_2O \tag{1}$$

.

Calcium carbonate solidifies and separates from the solution. A proper disposal of $CaCO_3$ sludge reduces environmental impact. Recycling or reusing sludge, such as soil stabilization with ordinary Portland cement (OPC), can be beneficial. Substituting $CaCO_3$ sludge for unqualified crushed rocks can decrease carbon emissions. Wiwattanachang et al. (2023)[6] found that by substituting unqualified crushed rocks with $CaCO_3$ sludge the mechanical qualities of soil-cement could be enhanced. Controlling the OPC constituient to a low ratio of no more than 3% by weight is the main factor that causes hydration reactions to bond other composites together.

Although calcium carbonate sludge has shown potential as a stabilizing material in road construction, there is a lack of comprehensive research on its long-term performance, environmental impacts, and compatibility with different pavement types under varying climatic and loading conditions. Furthermore, standardized guidelines for its treatment, dosage, and incorporation methods are not yet well-established, which limits its widespread adoption in civil engineering practices.

By employing a waste-to-wealth approach, the objective of this study is to investigate the effects of inclusion of CaCO3 sludge (10 to 30%) and ordinary Portland cement, OPC (1 to 3%) as partial replacement of the unqualified crushed rock on enhancing the subgrade material performance, optimizing cost efficiency and reducing carbon emissions. The research evaluates key parameters, including California Bearing Ratio (CBR) value, compaction efficiency, electrical resistivity, and cost benefit to determine the viability of CaCO3 sludge as a sustainable soil stabilizer. By leveraging a relationship between electrical resistivity and CBR value one expects to predict well the latter, an important parameter in pavement construction.

Experimental program

Materials

The materials used in this study include ordinary Portland cement (ASTM C150/C150M, 2022)[21]unqualified crushed rock and calcium carbonate sludge ($CaCO_3$), a byproduct of sugar refining processes, that frequently arises during the clarification and purification step.

The final carbonation mud resulting from sugar beet clarification processes contains mainly calcium carbonate (over 90%) among other minor constituents[22] . The calcium carbonate sludge has a specific gravity of 2.72, particle size ranging from 1 to 10 µm, and specific surface area of 0.228 m^2/g (see Table 2). Figure 3 displays photographs of the $CaCO_3$ sludge crystals taken by scanning electron microscopy (SEM) at 2,000 (Fig. 3a) and 20,000 (Fig. 3b) magnifications, respectively. In Fig. 3a the $CaCO_3$ sludge looks like small particles bonded in

Stabilizer	Environmental impact	Strength gain	Cost	Application suitability
$CaCO_3$ sludge	Low (waste reuse, no CO_2 emission)	Moderate (slow)	Low	Soft and silty soils
Lime	Moderate (CO_2 emissions)	Fast	Moderate	Clay-rich soils
Fly ash	Moderate (waste reuse, heavy metal risk)	Moderate to High	Low	Cohesive and sandy soils
Geopolymers	Low (low CO_2 emission, sustainable)	Very High	High	High-performance applications

Table 1. Comparison of some materials used in road construction.

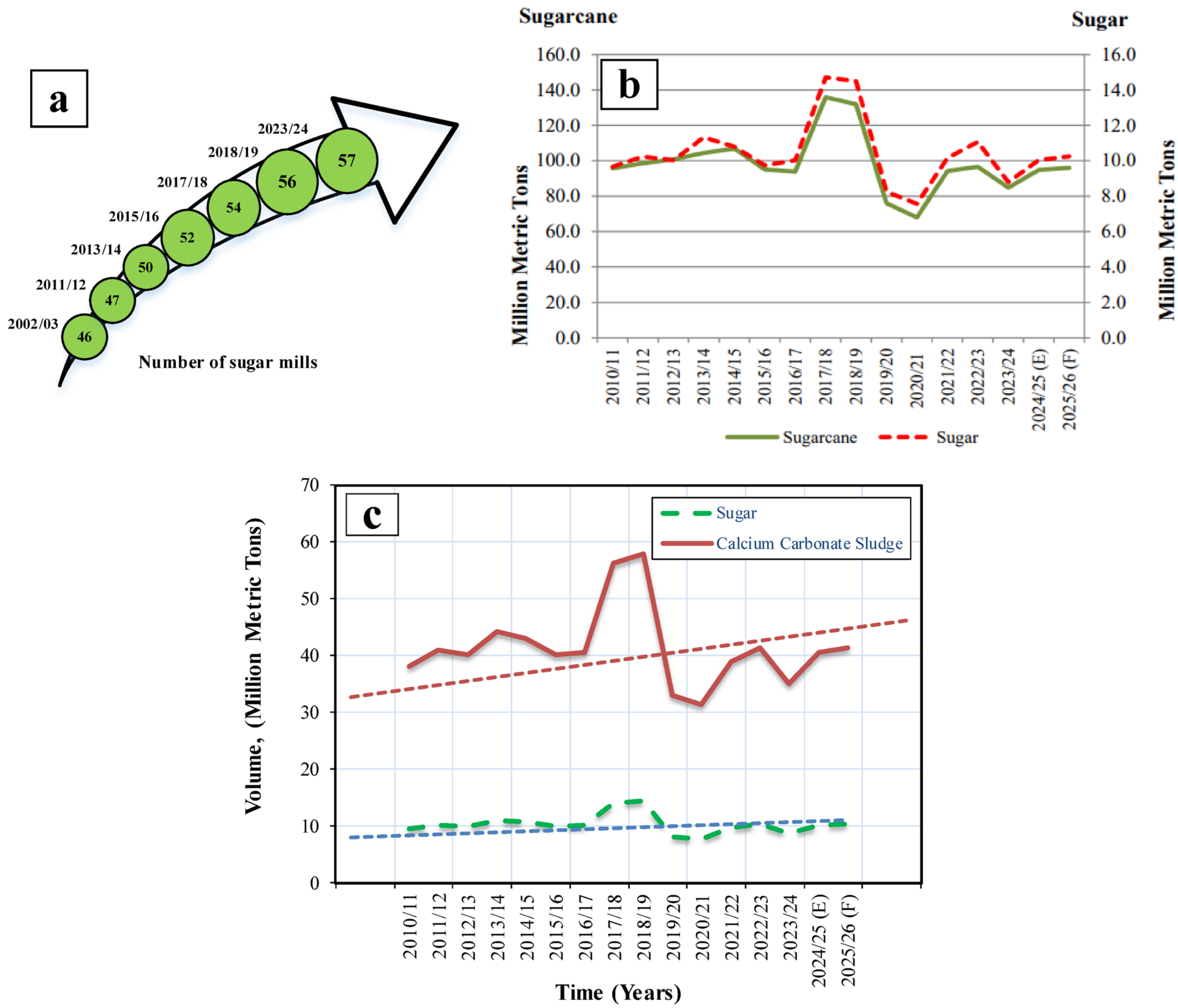

Fig. 1. Quantity of sugar mills (2002 to 2024) and production of sugarcane and sugar (2010/11 to 2024/25) inThailand: (**a**) The increasing trend of sugar mills from 2002 to 2024 after OCSB (2024)[18]; (**b**) The sugarcane and sugar production after USDA (2025)[19]where (E) is post estimates marketing year 2024/25, and (F) is post forecasts marketing year 2025/26; (**c**) The yearly amount of $CaCO_3$ sludge generated in relation with the sugar yield from 2010/11 to 2025/26.

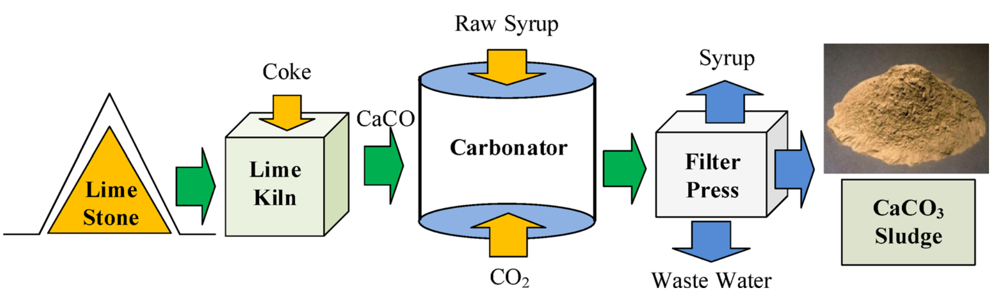

Fig. 2. The sugar refinery process.

lumps, and upon increasing the magnification by 10 times to 20,000 the $CaCO_3$ sludge exhibits a smooth surface and relatively well-defined geometric shapes as seen in Fig. 3b.

Table 2 shows the characteristics of the mixed subgrade constituents, including OPC, calcium carbonate sludge, unqualified crushed rocks, and water. 20% of the crushed rocks used in this experiment passed through sieve No.200, with the largest particle size being 45 mm. Table 3 shows the results of the semi-quantitative

Materials	Type	Characteristics
Ordinary Portland cement, (OPC)	Type-*I*	Specific gravity, Gs = 3.16; Specific surface = 3,150 cm^2/g
Calcium carbonate sludge, ($CaCO_3$)	Oxide powder	Specific gravity, Gs = 2.72; Particles size = 1–10 µm, specific surface area of 0.228 m^2/g
Unqualified crushed rocks	Well graded	The maximum size, D_{max} = 45 mm No. 200 sieve passing perc. = 20% Liquid Limit, LL = 16% Plasticity Index, PI = 12
Water	Tap water	pH = 7

Table 2. Characteristics of the mixed subgrade constituents.

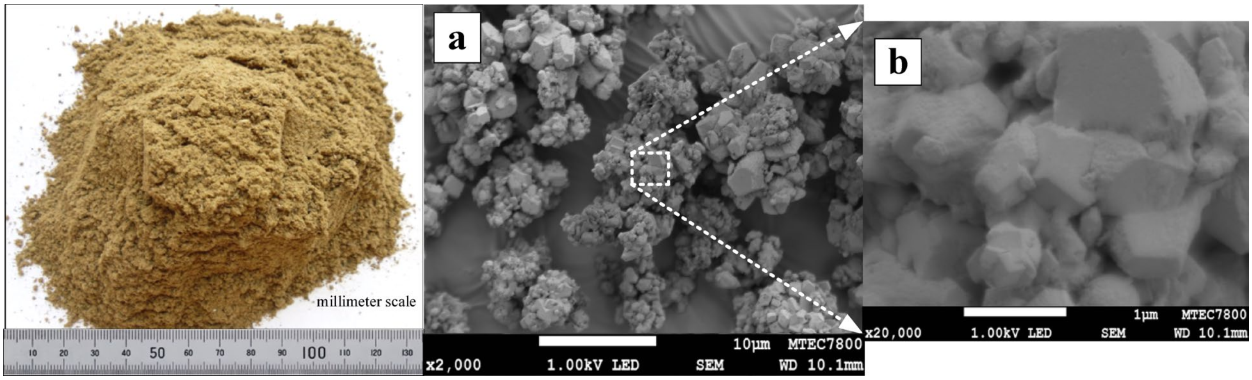

Fig. 3. Scanning electron microscopy (SEM) images of calcium carbonate ($CaCO_3$) sludge particles, which range in size from 1 to 10 µm. At lower magnification (**a**), particles appear in clusters; at higher magnification (**b**), the smooth surfaces and crystalline structure of individual particles are evident.

Materials	Chemical analysis (%)						
	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3
Ordinary Portland cement, OPC (wt%)	2.35	5.56	20.64	1.88	0.95	63.82	3.25
Calcium carbonate sludge, $CaCO_3$ (wt%)	0.51	0.13	0.77	1.04	0.01	97.24	0.16

Table 3. Result of the semi-quantitative chemical analysis of OPC and calcium carbonate sludge materials.

chemical analysis, using the X-ray fluorescence (XRF) method, indicating the similarities and differences between OPC and $CaCO_3$. Calcium oxide [CaO] is the main constituent in both OPC and $CaCO_3$ sludge, making up 63.82% and 97.24% of their respective chemical makeups. Silicon dioxide [SiO_2] is the most different between the two, making up 20.64% and 0.77%, respectively.

Quality control is crucial to assess suitability of $CaCO_3$ sludge for reuse, as impurities like organic matter, residual sugars, and phosphates can impact its performance. Moisture content significantly affects handling and weight, but this variability can be managed through drying before laboratory testing, ensuring consistency in quality and usability. The quality of $CaCO_3$ sludge samples can be checked based on their physical and chemical properties (see Tables 2 and 3) and it is quite uniform in this study testing program.

Mix design proportion

Table 4 details the mixture designs and the associated costs per cubic meter for 13 different mixtures used in the experimental program. These include one reference sample (SC_0-0) and three sets of four-sample batches, each having 10%, 20%, and 30% $CaCO_3$ sludge replacement for unqualified crushed rocks, respectively. The samples are labeled as SC_{x-y}, where x represents the percentage of mixed OPC, ranging from 0 to 3%, and y represents the percentage of $CaCO_3$ sludge, ranging from 10 to 30%.

The unit cost of mixtures incorporating $CaCO_3$ sludge ranges from 7.8 to 11.4 USD/m^3. Notably, most of these costs are below the 10 USD/m^3 benchmark for the mixture composed entirely of unqualified crushed rock (SC_0-0), suggesting a potential cost reduction of up to 28% (Table 5).

CBR testing and value

The California Bearing Ratio (CBR) is an empirical measure used primarily to assess the strength of subgrade soil and base materials for road and pavement design. In this study experimental program, firstly the $CaCO_3$ sludge and unqualified crushed rock samples were air-dried to remove excess moisture. Mixture is done by adding water based on the determined optimal moisture content (OMC) and mixed thoroughly to achieve a uniform

Mix no.	Ordinary Portland cement, OPC (%)	Calcium carbonate sludge, $CaCO_3$ (%)	Unqualified crushed rocks (%)	Cost per cubic meter, USD/m^3	Production emission, kg CO_2/ton
SC_0-0	0	0	100	10.0	135
SC_0-10	0	10	90	9.3	125
SC_1-10	1	10	89	10.0	133
SC_2-10	2	10	88	10.7	141
SC_3-10	3	10	87	11.4	149
SC_0-20	0	20	80	8.5	115
SC_1-20	1	20	79	9.2	123
SC_2-20	2	20	78	9.9	131
SC_3-20	3	20	77	10.6	139
SC_0-30	0	30	70	7.8	105
SC_1-30	1	30	69	8.5	113
SC_2-30	2	30	68	9.2	121
SC_3-30	3	30	67	9.9	129

Table 4. Mixture design of specimens with calcium carbonate sludge and the corresponding calculated cost and CO_2 emmission. The cost of OPC, $CaCO_3$ sludge, and unqualified crushed rocks is 80, 2.5 and 10 USD/m^3, respectively.

Stabilizer	Production emissions (kg CO_2/ton)	Transportation (kg CO_2/ton)	Total carbon emissions (kg CO_2/ton)	Cost per cubic meter, USD/m^3
Ordinary Portland Cement (OPC)	870–930	20–50	890–980	80
$CaCO_3$ sludge	0 (byproduct)	20–50	20–50	2.5
Unqualified crushed rocks	50–100	40–80	40–80	10

Table 5. Comparative carbon savings and cost of materials.

CBR value (%)	Relative strength/load-bearing capacity
0–5	Very poor (*weak soil, low strength*, e.g., *clay or peat*)
5–10	Poor to fair (*medium strength*, e.g., *silty soils*)
10–15	Good (*well-compacted granular soils*)
15–20	Excellent (*strong materials like crushed stone or gravel*)

Table 6. The relationship between CBR and strength.

moisture distribution. The mix designs and denotations of the tested samples are shown in Table 6 together with their corresponding calculated production emmission of carbon dioxide (kg CO^2/m^3). Compaction is conducted using a CBR mold with a detachable base plate and collar. For the testing under soaked conditions, the sample was immersed in water for 4 days, and then drained to remove the excess water before being placed in the loading frame and plunger.

The CBR test is carried out according to ASTM D1557 (2012)[23]. It involves compacting a soil sample into a cylindrical mold and then measuring the pressure required to penetrate the soil with a standard-sized piston. The pressure is compared to the pressure needed to achieve the same penetration in a standard crushed stone material. The CBR value is defined as follows:

$$CBR = \frac{P}{P_{std}} \times 100. \quad (2)$$

where: CBR is the CBR value (in %), P is the measured pressure on soil mixture sample; P_{std} is the standard pressure, which is 56,000 ft-lbf/ft^3 (2,700 kN-m/m^3) in this study.

CBR value provides an indirect indication of a soil's shear strength and bearing capacity, a higher CBR value means the material resists penetration better, indicating greater shear strength, higher bearing capacity, and better load-spreading ability (see Table 5). In general, the higher CBR the higher UCS (Unconfined Compressive Strength), but this relationship is nonlinear and depends on soil type, moisture content, and compaction level. Applications of CBR include: (*i*) Pavement Design: CBR values are used to design thicknesses for roads and runways, ensuring that the pavement layers are strong enough to handle the expected traffic loads; (*ii*) Soil

Assessment: CBR values are used in evaluating the suitability of a soil as a foundation material and deciding whether soil improvement techniques are necessary.

Electrical resistivity testing

A material's innate ability to withstand the flow of electricity is known as its electrical resistivity. Figure 4a illustrates the process of placing the soil-cement admixture into a 0.15-meter-diameter and 0.30-meter-long PVC mold. This investigation bases its setup to measure the electrical resistivity of a $CaCO_3$ sludge-mixed cylindrical sample on a design by Wiwattanachang et al. (2023)[6] with the help of the Wenner array that consists of four steel needle electrodes, 6 mm in diameter and 30 mm in length, co-linearly installed on the sample surface, and penetrated about 10 mm into the sample. Regarding the penetration depth of the electrodes into the tested samples for resistivity measurements Giao et al. (2003)[24] had investigated the Busan soft clays and found that for various electrode penetrations (i.e., 0.1, 1, 2, 3, 4, 5, and 6 cm), the measured electric resistivity values were practically identical. In a temperature-controlled laboratory at 25 °C, the surface of a soil cement sample receives the application of chemical curing compounds by the Sika MP-10 series. This membrane prevents moisture evaporation and retains water in the soil-cement and $CaCO_3$ sludge mixed sample, ensuring its hydration.

The measurements of current intensity, I (mA), and the potential difference, ΔV (mV), between potential electrodes M and N (see Fig. 4a), are used to calculate the apparent electrical resistivity, ρ_a (Ωm), as follows:

$$\rho_a = k\frac{\Delta V}{I} \tag{3}$$

$$k = \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)}. \tag{4}$$

Where: k is called the geometric factor of the electrode array and is defined by Eq. 3b below. In this study, the Wenner array consisting of four equally-spaced electrodes was employed, for which $k = 2\pi a$, where a is the spacing between two adjacent electrodes and equal to 0.05 m as shown in Fig. 4a.

The finite size of laboratory core samples strongly influences the electrical resistivity measurements that need to be corrected[24,25]. Morris et al. (1996)[25]'s chart was used for correcting the apparent resistivity (ρ_a) of a small cylinder-shaped sample as shown in Fig. 4b.

Results and discussions

Soaked CBR value versus the $CaCO_3$ sludge and OPC mixing proportion

The CBR value measures a material's resistance to standard plunger penetration under controlled density and moisture conditions. The cement content promotes hydration reactions in different amounts, which leads to the formation of a solid mass with a higher CBR value as seen in Table 7; Fig. 5, where one can see that the CBR value is decreasing with the increasing $CaCO_3$ sludge from 0, 10%, 20–30%, and with the increasing OPC from 0, 1%, 2–3% in the mixture, respectively. Higher $CaCO_3$ sludge seems to lead to an overabundance of fine particles, which reduce interparticle friction and weakens the mix's structural integrity. It can also increase void spaces, resulting in a less compact and weaker subgrade. While OPC aids in strengthening, high sludge content dilutes the availability of cementing agents, limiting the formation of strong C-S-H bonds.

Reacting calcium carbonate sludge with OPC produces calcium silicate hydrate (C-S-H), an important component of the hardened paste that gives cement-based constructions their strength as seen in the following equation:

$$\mathrm{CaCO_3} + 2\mathrm{SiO_2} + 6\mathrm{H_2O} \rightarrow \text{C-S-H} + \mathrm{CO_2}. \tag{4}$$

This reaction facilitates the hardening and strength enhancement of concrete. Calcium carbonate ions in cement combine with silicate ions to produce calcium silicate hydrate, a gel-like substance that fills the pores and gaps in the cement paste. This gel-like material gradually combines with the surrounding cement particles to form a more rigid, crystalline structure that endows the product with strength and longevity[26].

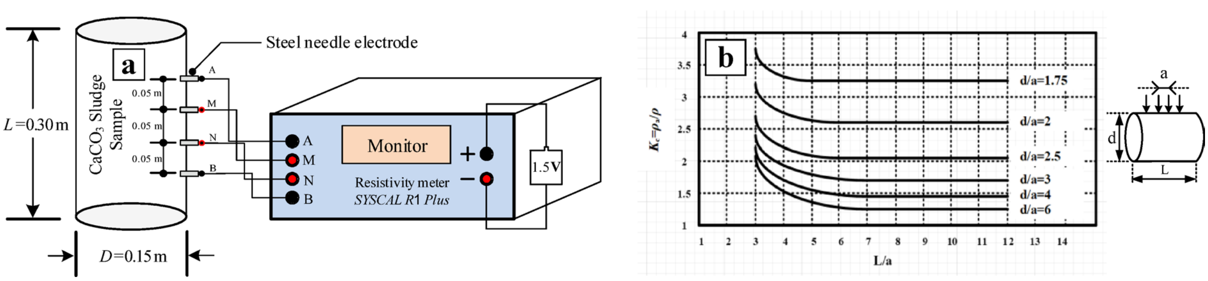

Fig. 4. Electrical resistivity measurement on $CaCO_3$ sludge sample: (**a**) Testing setup with the Wenner array; (**b**) Correction of resistivity measurements by the Wenner array for a cylindrical sample of d diameter, L length (after Morris et al., 1996)[25].

Samples	SC_0-0	SC_0-10	SC_0-20	SC_0-30	SC_1-0	SC_1-10	SC_1-20	SC_1-30
γ_d (gm/cc)		2109	2020	1919	2290	2114	2027	1923
Wc (%)	6.1	6.9	7.9	8.6	5.6	6.3	7.8	8.6
UCS (MPa)	0.67	0.25	0.18	0.09	1.08	0.83	00.44	0.17
CBR (%)	29	29	18	12	112	83	78	47
ρ (Ωm)	12	10	9	7	33	22	19	12
ρ_a (Ωm)	21	17	16	13	58	38	33	21
Samples	**SC_2-0**	**SC_2-10**	**SC_2-20**	**SC_2-30**	**SC_3-0**	**SC_3-10**	**SC_3-20**	**SC_3-30**
γ_d (gm/cc)	2295	2122	2033	1936	2306	2134	2044	1957
Wc (%)	5.4	6.5	8.0	8.8	5.2	6.7	8.2	9.0
UCS (MPa)	2.15	1.61	1.00	0.53	3.37	2.35	1.48	0.81
CBR (%)	197	113	89	71	285	146	104	90
ρ (Ωm)	46	35	29	25	68	35	28	24
ρ_a (Ωm)	79	60	50	43	117	61	49	42

Table 7. The results of testing results, including dry density, g_d (for soaked conditions), water content, Wc (%), unconfined compressive strength (UCS), CBR values, measured (ρ_a) and corrected resistivity (ρ).

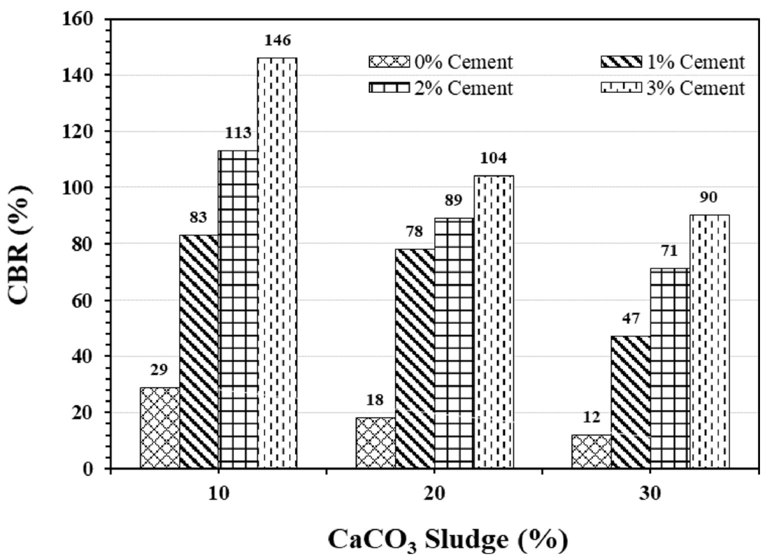

Fig. 5. CBR value (soaked condition) versus $CaCO_3$ sludge and OPC mix proportions.

While hydrates from a cement grain may help hold soil particles together and make the aggregate last longer, OPC is a major cause of the carbon footprint[27,28]. Figure 5 illustrates that the quality of subgrades must incorporate CBR values while also taking the unit price into account as indicated in Table 4 As a result, this research methodology aims to minimize OPC consumption and optimize $CaCO_3$ sludge utilization, which can be considered a viable strategy, particularly in the context of waste management.

Influence of $CaCO_3$ sludge and OPC on compaction enhancement

$CaCO_3$ sludge when compacted together with cement and unqualified crushed rock can improve the stability of the soil-cement mixture. According to Wiwattanachang et al. (2023)[6]it can strengthen the cement's binding qualities and increase its load-bearing capacity. This study fcuses more on the influence of this mixing on compaction enhancement by an increase in CBR value and a decrease in dry density or blow number.

Figure 6 shows the effect of $CaCO_3$ sludge and OPC on dry density and CBR values. For example with 10% of $CaCO_3$ sludge and the OPC volume increasing from 0%, 1%, 2–3%, the CBR value has increased from 29 to 83, 113, and 146, respectively (see Table 7). A higher OPC volume causes the soil's void ratio decreasing because the OPC fills the pore space in the material by reacting with water[29]. So, by using OPC (with a limited dose) and $CaCO_3$ sludge (up to 30%) replacing some percentages of unqualified crushed rocks one can expect an optimal balance in compation enhancement (higher CBR value, lower dry density or smaler blow number) as well as a reduction in cost and $CaCO_3$ emission of the mixed material (see Tables 4 and 7).

By comparing the test results of the SC_0-0 sample with those of SC_0-10, SC_1-10, SC_2-10, and SC_3-10 (see sample denotations in Table 4), it is observed that replacing 10% of unqualified crushed rock with $CaCO_3$ sludge

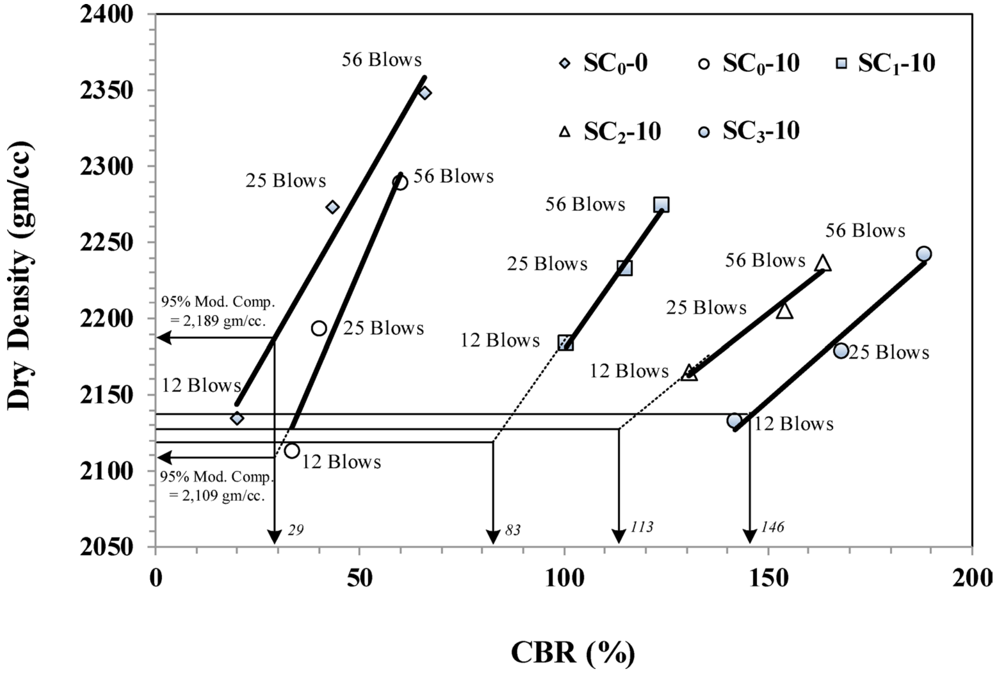

Fig. 6. The relationship between CBR value, blows and dry density of the soil- CaCO3 sludge mix found by this study.

(SC_0-10) reduces the dry density by 80 g/cc from 2,189 to 2,109 g/cc while the CBR value remains unchanged at 29%.

As shown in Fig. 6, both dry density and CBR values increase with higher compaction energy (from 12 to 56 blows). When combining 10% $CaCO_3$ sludge with 1–3% OPC, the dry density at 56 blows varies across the samples, and namely: 2,114 g/cc (SC_1-10), 2,122 g/cc (SC_2-10), and 2,134 g/cc (SC_3-10), indicating that the addition of OPC helps offset the density reduction caused by sludge incorporation.

The testing results indicated that the influence of $CaCO_3$ sludge and OPC can improve compaction efficiency and higher CBR value compared to conventional materials[6,30]. The lower blows number is due to the influence of $CaCO_3$ sludge, which implies a higher soil compaction efficiency. The action of $CaCO_3$ sludge reduces density, which is inversely proportional to water absorption[31].

Compaction effort at 56 blows/layer versus 12 blows/layer

The number of blows per layer, for example, 12, 25, and 56, reflects the quantity of mechanical energy applied to the soil mass throughout the CBR testing procedure. The frequency of soil compaction directly influences the rise in CBR values[32].

Comparing compaction at 56 blows and 12 blows provides insight into how different compaction efforts affect soil strength. Higher compaction (56 blows) generally increases soil density, reduces voids, and enhances CBR values. Conversely, lower compaction (12 blows) helps assess whether additional effort yields significant strength gains or if the soil reaches a compaction limit where further effort provides minimal improvement. Understanding this relationship is essential for determining the optimal compaction effort required to achieve the desired soil strength in pavement construction.

Figure 7(a) shows that for the samples of 100% unqualified crushed rocks (denoted SC_0-0) the average pressure ratios at 56 blows/layer versus 12 blows/layer is 3.25 and 1.75, on average value, for the soaked (S) and unsoaked (US) conditions, respectively, which means that the compaction under the soaked conditions requires a greater amount of energy for a higher pressure ratio at compaction. Figure 7(b) shows that the results become different when admixtures are made with $CaCO_3$ sludge percentage ranging from 10%, 20–30%, and namely, due to the addition of $CaCO_3$ sludge the pressure ratios at 56 blows/layer versus 12 blows/layer is quite similar for three sets of samples SC_0-10, 20, 30 regardless of whether the sample was in soaked (S) or unsoaked (US) conditions.

Baker et al. (2005)[33] found that samples containing lime sludge exhibited superior compaction under wet and dry conditions. However, they noted that soil-cement becomes more vulnerable to strength loss when exposed to water, a critical consideration in pavement design and construction. In contrast, the results of our study demonstrated that incorporating $CaCO_3$ sludge into the pavement admixture preserves compaction performance even under soaked conditions.

Electrical resistivity monitoring

Advances in geotechnical and geo-environmental practices have made soil electrical resistivity an attractive property due to its non-destructive nature and economic viability (e.g., Giao et al., (2003)[24]Zhu et al.,

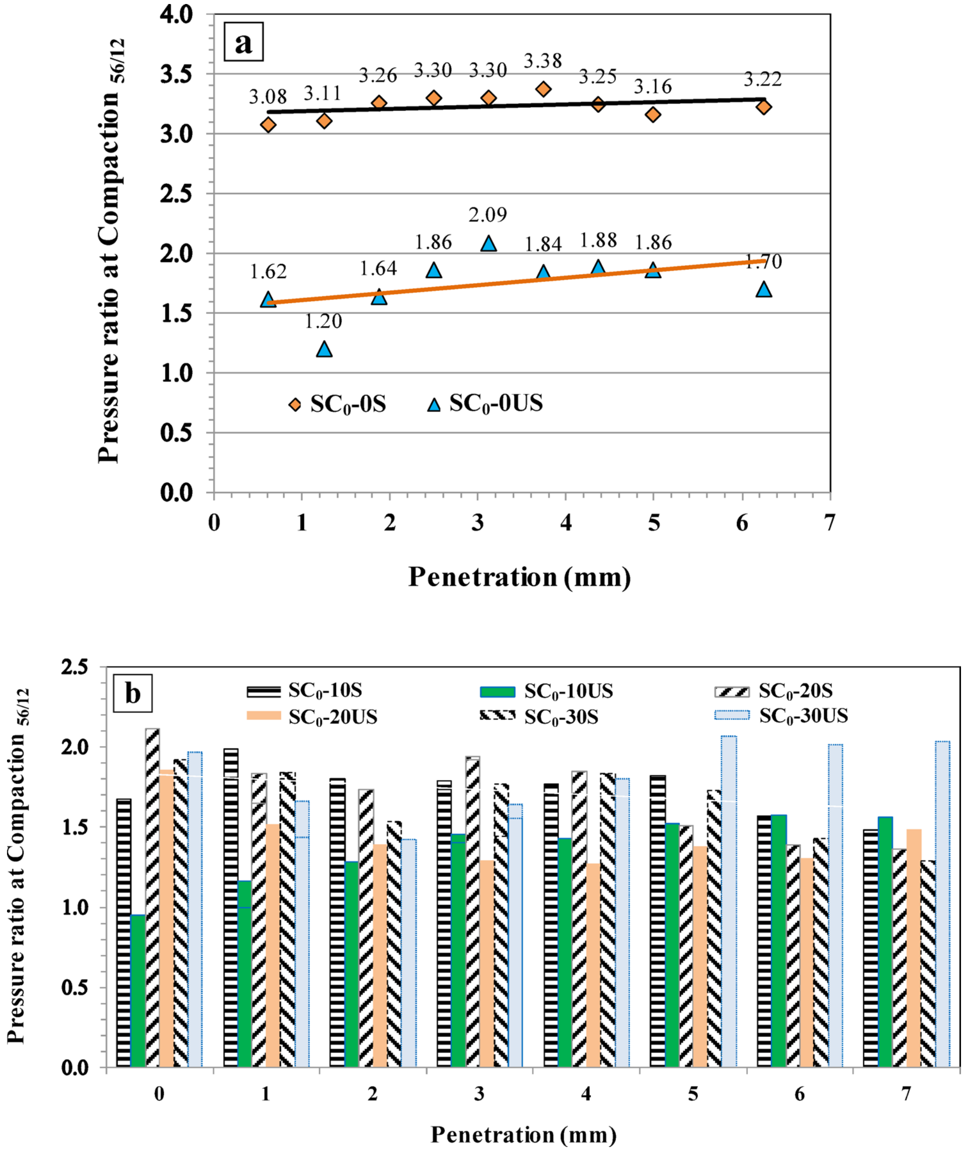

Fig. 7. Influence of $CaCO_3$ sludge percentage on the pressure ratio at compaction 56/12 blows in the soaked (S) and unsoaked (US) conditions: (**a**) for the specimens made of only unqualified crushed rock; (**b**) for the specimens mixed with CaCO3 (10%, 20–30%).

(2015)[34]López and Mansilla, (2017)[35]Wiwattanachang et al., (2023)[6]). Electric resistivity is proved to be able to correlate well with a good number of geotechnical properties of soils, rocks and other material types. For non-cohesive soils, electrical resistivity is a potentially useful alternate method for determining the degree of compaction[36]. Akintorinwa and Oluwole (2018)[37] have investigated an empirical relationship between CBR values and electrical resistivity of shallow soils of 1 to 2 m deep.

The samples for resistivity measurements in our study have a diameter (d) of 0.15 m, a length (L) of 0.30 m, and the measuring Wenner array employed has an electrode spacing (a) of 0.05 m. The Morris's correction as shown in Fig. 4b yields a correction coefficient of K_c = 1.73 for $d/a = 3$ and $L/a = 6$.

Figure 8 plots a relationship between CBR value and the corrected electrical resistivity (ρ). The correlation between CBR (both soaked and unsoaked) and resistivity (corrected) values is fitted by Eq. 5 below with a very good correlation coefficient $R^2 = 0.925$.

$$\text{CBR (\%)} = 1.2692\rho^{1.3066} \quad (5).$$

Where CBR (%) represents the California bearing ratio (CBR) values; ρ (Ωm) is the corrected electrical resistivity. The differences in soil type, mix proportions, moisture content, and compaction are the factors influencing this relationship[38,39].

Consequently, one can use electrical resistivity as a proxy to estimate a soil's CBR, though direct testing for both parameters is usually required for a more accurate assessment. As Eq. (5) could produce consistent

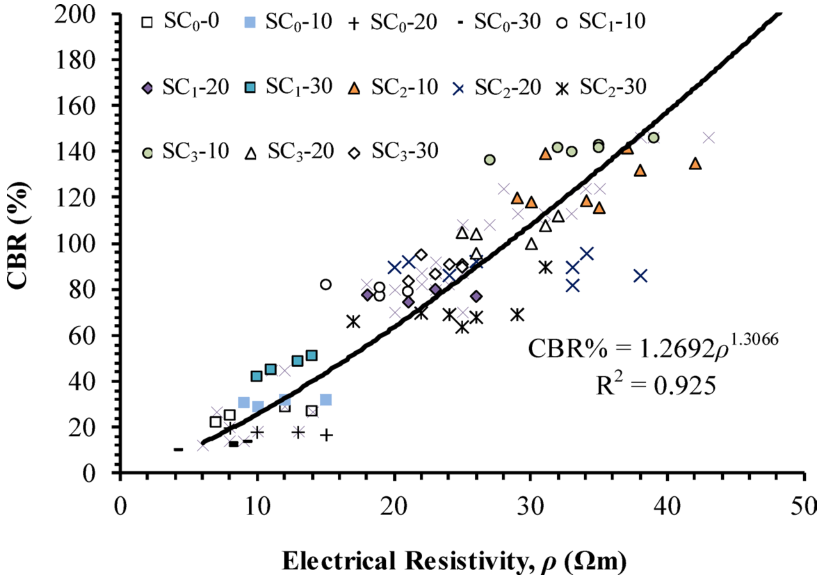

Fig. 8. Relationship between CBR value and electrical resistivity.

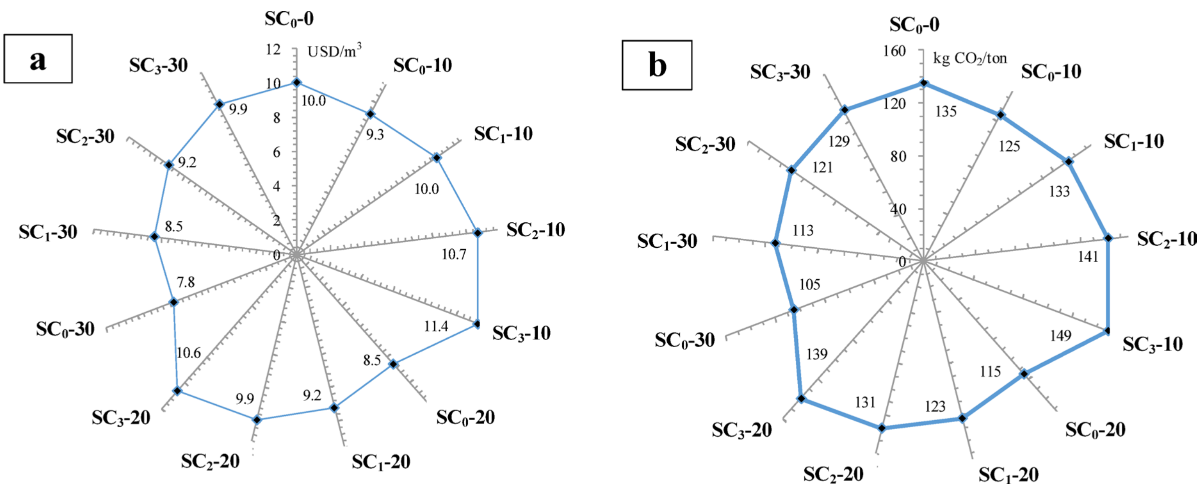

Fig. 9. Cost and carbon saving analysis: (**a**) Cost per cubic meter (USD/m^3); (**b**) Carbon saving (kg CO_2/ton).

and dependable outcomes, measuring electrical resistivity can be a standard practice for quality monitoring of pavements made of mixed subgrade materials.

Cost-benefit analysis

The nominal cost of OPC, $CaCO_3$ sludge, and unqualified crushed rocks is 80, 2.5 and 10 USD/m^3, respectively.A cost-benefit analysis was conducted in this study to compare the economic feasibility of using $CaCO_3$ sludge and OPC against traditional subgrade materials, considering both material costs and potential long-term savings from improved road durability (see Tables 4 and 5).

The traditional subgrade material of 100% unqualified crashed rock (SC_0-0) has a base price of 10 USD/m^3. In the case of using 10% $CaCO_3$ sludge (SC_0-10) to replace unqualified crushed rocks the unit price will lower to 9.3 USD/m^3 (see Table 3). Despite adjustments to the mixture to produce a higher-quality soil-cement, the cost of SC_1-10 remains unchanged.

Figure 9 shows that OPC is the primary factor that has the greatest negative impact on pricing. In other words, the higher cost of subgrade materials will be proportional to the increase of OPC percentage in the mix. As a result, the mixtures of SC_1-30 or SC_2-30, which costs 8.5 USD/m^3 and 9.2 USD/m^3, would be a more cost-effective choice comparing to that of the traditional subgrade material (SC_0-0) that costs 10.0 USD/m^3. Thus, these options represent not only a high-quality subgrade material, but also with a cost reduction of 15% and 8% respectively. The potential benefits of using $CaCO_3$ sludge and OPC in subgrade materials can be maximized, contributing to more sustainable and efficient road construction practices.

Materials	Benefit			
	CBR value	Compaction efficiency	Cost per unit	Environmental Impact
Ordinary Portland cement, OPC	✓	–	✖	✖
Calcium carbonate sludge, $CaCO_3$	✖	✓	✓	✓

Table 8. Benefits brought by inclusion of OPC and $CaCO_3$ sludge in the mix design.

The results of this research can serve as a reference for improving soil compaction efficiency, promoting zero waste, and developing high-quality subgrades built from recycled materials like calcium carbonate sludge from the sugar refinery industry. If the total amount of $CaCO_3$ sludge up to 41 MMT (2.5 USD/m^3) generated by Thailand's sugar refinery industry in one year of 2024 (see Fig. 1c) can be fully used to replace the unqualified crashed rock (10.0 USD/m^3) in road construction, a financial gain of 4.1 mil. x 7.5 = 307.5 mil. USD could be expected.

Comparison of SC_0-0, SC_1-30, and SC_2-30 in Fig. 5 revealed that SC_2-30 achieved the highest CBR value at 71%, while SC_1-30 and SC_0-0 recorded 47% and 29%, respectively. Table 4 indicates that, among the mixed samples, SC_1-30 had the lowest unit cost at 8.5 USD/m^3, followed by SC_2-30 at 9.2 USD/m^3, and SC_0-0 at 10 USD/m^3. The results suggest that incorporating $CaCO_3$ sludge and OPC enhances subgrade quality, leading to improved performance at a lower cost while adding value to waste materials. Therefore, maximizing $CaCO_3$ sludge content while minimizing OPC usage is recommended. Among the 12 mix designs evaluated, SC_1-30 emerged as the most cost-effective and optimal choice. The practical importance of this study lies in its evaluation of cost savings, enhanced compaction efficiency, and lower CO_2 emission through the use of a industrial waste like $CaCO_3$ sludge in road pavement construction as seen Fig. 9a, b; Tables 7 and 8.

Conclusions and recommendations

In this study, a total of 12 (3 × 4) cylindrical mixed specimens of 15-cm diameter and 30-cm length were prepared and tested by CBR ad electric resistivity measurements in addition to a benchmark sample of 100% unqualified crushed rock. These samples consisted of unqualified crushed rock mixed with 10%, 20%, and 30% of $CaCO_3$ sludge and 0%, 1%, 2%, and 3% of OPC as partial substitutes. The main findings of the study can be summarized as follows:

1. The CBR values of the tested samples in the soaked conditions were found to be increasing with the increasing OPC percentage from 0, 1%, 2–3% and decreasing with the increasing CaCO3 sludge percentage from 0, 10%, 20–30%, respectively. However, the mixtures of 10% or higher of $CaCO_3$ sludge can attain satisfactory compaction performance in both soaked and unsoaked conditions as seen in Fig. 5. The results of our study demonstrated that incorporating $CaCO_3$ sludge into the pavement admixture preserves compaction performance even under soaked conditions.
2. By using OPC (with a limited dose from 1 to 3%) and CaCO3 sludge (up to 30%) to patially replace unqualified crushed rocks in the mix designs, we could find an optimal balance in compaction enhancement and efficiency (higher CBR value, lower dry density or smaller blow number), reduction in cost and CaCO3 emission (see Tables 4 and 7). For example, for the samples having 10% CaCO3 sludge and 0%, 1%, 2–3% OPC the CBR value has increased from 29 to 83, 113, and 146, respectively.
3. The addition of $CaCO_3$ sludge alone may not increase the strength, but can help lowerin the dry density, thus increasing the compaction efficency. For example, by comparing the testing results of the unmixed sample (SC_0-0) with a sample mixed with 10% of CaCO3 sludge (SC_0-10 as seen in Table 4) one can observe a reduction in dry density from 2,189 to 2,109 gm/cc (a difference of 80 gm/cc), while the CBR value remained the same at 29%. It is worth noting that both dry density and CBR value increase with the increasing blow number ranging from 12 to 56 times as seen in Fig. 6.
4. A strong relationship between CBR and electric resistivity of the mixed subgrade material was found in Eq. 5, i.e., CBR (%) = $1.2692\rho^{1.307}$, with a very good correlation coefficient $R^2 = 0.925$, allowing a good prediction of CBR value based on quick and easy measurements of resistivity.
5. In term of cost analysis, a comparison of SC0-0 (only unqualified crushed rock) with mixed samples of SC1-30, and SC2-30 (Fig. 5) revealed that SC2-30 achieved the highest CBR value at 71%, while SC1-30 and SC0-0 recorded 47% and 29%, respectively. As seen in Table 4 SC1-30 has the lowest unit cost at 8.5 USD/m^3, followed by SC2-30 at 9.2 USD/m^3 and SC0-0 at 10 USD/m^3. Among the 12 mix designs evaluated, SC1-30 emerged as the most cost-effective and optimal choice. Thailand in 2024, as seen in Fig. 1c, produced an amount of CaCO3 sludge up to 41 MMT (2.5 USD/m3) that, if fully used to replace the unqualified crashed rock (10.0 USD/m3), an financial gain is estimated as 41 million $m^3 \times 7.5$ USD = 307.5 million USD. The results suggest that incorporating CaCO3 sludge and OPC enhances subgrade quality, leading to an enhanced compaction at a lower cost while adding value to waste materials. Therefore, maximizing CaCO3 sludge content while minimizing OPC usage is recommended.
6. Finally, some key takeaways of this study can be summarized as follows, i.e., (a) *Valorization of a industrial waste*: $CaCO_3$ sludge, generated during sugar refining, poses storage and environmental issues, for which a sustainable solution was proposed in this study by incorporating this waste into subgrade materials, aligning with geoenvironmental strategies for a greener sugar industry in Thailand and beyond; (b) *Optimized mixture composition*: including 10–30% $CaCO_3$ sludge, 1–3% Ordinary Portland Cement (OPC), and 67–100% unqualified crushed rocks by weight with the SC_1-30 mixture (30% of $CaCO_3$ sludge and 1% of OPC) being

the best; (c) *Enhanced compaction capacity and efficiency*: the inclusion of calcium carbonate sludge and OPC improved the CBR value and lower the dry density/blow number; (d) *Electrical resistivity as a non-destructive testing tool*: the electrical resistivity measurements showed a strong correlation with CBR values, suggesting, thus, in practical implication, this method could offer a time-saving and cost-effective approach for on-site quality control during road pavement construction; (e) *Geoenvironmental and economic benefits*: Utilizing $CaCO_3$ sludge in subgrade materials could address waste management issues in the sugar industry (waste reduction); The proposed approach reduces reliance on traditional materials, potentially lowering construction costs and environmental impact (cost efficiency).

7. This reseach work demonstrates a viable pathway for integrating industrial waste into infrastructure development, promoting sustainability and resource efficiency in the road construction sector. Utilizing CaCO3 sludge has numerous advantages. The availability and quality of CaCO3 sludge are important considerations. For a wider acceptance of the proposed innovative approach, it is crucial to have regulations, business involvement, and interdisciplinary research collaborations.

Data availability
The datasets used and/or analyzed during the current study available from the corresponding authors on reasonable request.

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Author contributions
NW: Conceptualization, Methodology, Data curation, Formal analysis, Writing- original draft, Validation. CV: Investigation, Methodology, Writing - review & editing. AK: Investigation. PHG: Formal analysis, Result Discussion, Writing - review & editing.

Declarations

Competing interests
The authors declare no competing interests.

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