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Assessing the potential of dolomite by-products as sustainable geomaterials for road embankment applications

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Abstract. Dolomite by-products, often considered waste spillages from mining sedimentary rock deposits, represent a significant environmental challenge due to their improper disposal. This study investigates the potential use of these by-products as sustainable geomaterials for road embankments. Laboratory tests conducted in accordance with ASTM standards evaluated the microfabric structure, particle size distribution, compaction behavior, load-bearing capacity, and permeability characteristics of dolomite by-products. Results classify the material as well-graded silty sand with low plasticity with USCS symbol of SW-SM. It falls under the AASHTO group A-1-b, indicating an excellent to good general subgrade rating. Microstructural analysis reveals angular particles with sharp edges, promoting interlocking and strength, while chemical analysis indicates a composition dominated by oxygen and carbon with traces of magnesium and calcium. The material achieves a maximum dry unit weight of 18.31 kN/m³ at an optimum moisture content of 8.34%, with California Bearing Ratio (CBR) values ranging from 6% to 19%, rating it as a fair subbase material. Permeability tests show medium drainage characteristics with coefficients ranging from 0.0187 cm/sec to 0.0417 cm/sec suitable for subgrade applications with adequate drainage. Predictive models for hydraulic conductivity and load-bearing capacity provide practical tools for field applications. Comparative analysis highlights the material's performance as superior to clayey subgrades and comparable to sandy subgrades. This study establishes dolomite by-products as a viable alternative geomaterial for road construction, addressing waste disposal issues while promoting sustainable construction practices. Limitations include the absence of shear strength and compressibility data, suggesting avenues for further research.

Keywords: compaction behavior; dolomite by-productpermeability; geomaterial; load-bearing capacity

1. Introduction

Dolomite, chemically represented as $CaMg(CO_3)_2$, is a carbonate mineral that is a critical raw material in numerous industrial applications, including steel manufacturing, glass production, ceramics, and agriculture. It is typically found within dolostone, a carbonate sedimentary rock that comprises dolomite as its primary mineral component. Along with limestone, dolostone is classified as one of the two principal types of carbonate rocks (Mehmood *et al.,* 2018).

The dolomite formation is categorized into primary dolomite and secondary dolomite based on its genesis. Primary dolomite is directly precipitated from aqueous solutions under specific geochemical conditions. In contrast, secondary dolomite undergoes a transformation process known as dolomitization, during which calcite is dissolved, and magnesium ions replace calcium ions within the mineral structure.

Cebu Province, located in the Philippines, is recognized as one of the significant sources of mineable dolomite deposits globally. The deposits are situated predominantly in forested mountainous regions of a town in Cebu, adjacent to residential areas and bordering the Cebu Strait. A mining operation in this area extracts raw dolomite, which is subsequently processed and distributed in varying particle sizes to meet industrial demands (Mayol 2020). Dolomite plays a versatile role in industrial processes. Its typical applications include use as a sintering agent and flux material in iron and steel production, assisting in impurity removal during smelting. Additionally, dolomite is integral to manufacturing glass and ceramics and is widely used as a fertilizer additive and soil enhancer in agricultural applications.

The dolomite in Cebu is classified as secondary dolomite, primarily formed through magnesium ion substitution in calcite. The geological conditions in Cebu indicate that dolomite formation is influenced mainly by the evaporation of seawater within a supratidal environment. This process facilitates significant mineralogical changes, specifically the transformation of calcite into dolomite. This localized mechanism highlights the distinct geological factors that contribute to the region's unique characteristics of dolomite deposits.

Dolomite mining in the area has been conducted for over 40 years. The extraction of dolomite in Cebu employs open-pit mining techniques. This method involves the removal of dolomite deposits situated several meters below the surface. The mined material undergoes grain particle

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sizing and screening to produce various grades and particle sizes of dolomite for specific industrial uses. During mining, low-grade dolomite with a high clay content, considered an impurity, is generated as a by-product. These by-products are often repurposed as mineral fillers, functioning similarly to fine-grained aggregates like sand. Despite the systematic processing methods, significant material loss occurs during the transportation of dolomite via conveyor belts. Estimates indicate that 50–100 tons of dolomite spillages are generated during transport, raising concerns over environmental impacts such as water pollution, coral reef degradation, and land-use inefficiencies. These waste materials, often stockpiled without practical use, represent a pressing environmental challenge and an underutilized resource.

Though economically beneficial, mining activities produce various adverse effects on the environment because of the enormous waste produced at mining sites. The disposal of mining by-products, such as the dolomite by-products, poses environmental risks and highlights the need for sustainable practices in mining and construction. One possible option to reduce its volume in the environment is to utilize mining waste as an alternative geomaterial in construction.

Mining wastes from other minerals have shown promise as alternative construction materials. The study of Adajar *et al.* (2017) proves that waste materials from aggregate quarries can be used as fine aggregates in concrete mixes, demonstrating strength properties suitable for structural applications. Gold mine tailings were considered to create geopolymer binders, a viable substitute for cement in concrete production (Uy *et al.* 2021). Waste in producing metallic sulfide was utilized as a component in the paste-fill material to address the disposal issues in the lead and zinc underground mines (Ugurlu and Ozturk, 2021). Adding 20% fine marble waste improved the geotechnical characteristics of dune sands, including compaction and load-bearing capacity (Qureshi *et al.* 2022). A study on dimension limestone wastes as fine aggregate replacement in concrete to assess hardened concrete's durability and strength performance proved that mining products can replace traditional aggregates (Panganiban and Adajar 2023). The reviewed studies underscore the potential of mining by-products to be repurposed into valuable materials, mitigating disposal issues while promoting sustainable development. The findings highlight that mining by-products can be used as alternative construction materials. However, research on dolomite by-products, particularly their geotechnical applications, remains scarce. It is still unclear whether dolomite by-products can be sustainable and cost-effective alternatives to traditional embankment materials in roadway construction.

Previous studies have focused on the use of high-quality dolomite as construction materials. Sernas *et al.* (2016) conducted a study to assess high-quality dolomite aggregates as asphalt-wearing layer aggregates and to build rut-resistant asphalt mixes using dolomite stones. The results of the tests revealed that the bitumen-aggregate adhesion characteristics were good. The resistance to permanent deformation of asphalt mixes is accomplished by creating coarser gradation mixes with a larger percentage of air voids than standard asphalt mixes for the wearing layer. Wasilewska *et al.* (2017) stated that the primary function of these high-quality dolomite aggregates is to fill the voids in the aggregate skeleton to achieve a denser mixture along with improving the cohesion of the asphalt binder and stability of the mix. Kumar (2016) investigated concrete's fresh and hardened characteristics when partially replaced with dolomite powder. Results showed that in low percentages, from 5 to 15%, dolomite additives play the role of an active component or even act as a cement replacement. Rudnicki (2022) explored using dolomite crushed from creamy to yellow sedimentary rocks as an aggregate in concrete pavement to reduce the carbon footprint in road construction. Results showed that the highest bending parameters were obtained for concrete with dolomite aggregate, leading to a 19% reduction in carbon footprint when the locally available dolomite aggregate was used in concrete pavement. The study of Gusain *et al.* (2023) utilized dolomite to partially replace cement in concrete to introduce an eco-friendly construction material. A 15% cement replacement by dolomite produced the maximum compressive strength.

While high-grade dolomite is widely utilized in construction, particularly for road surfaces and other structural applications, the potential of dolomite by-products as geomaterials for road embankments remains underexplored. Existing research primarily focuses on high-grade dolomite, leaving a significant gap in understanding whether dolomite by-products, often treated as waste, possess similar geotechnical characteristics suitable for road construction. Addressing this gap is critical for promoting sustainable waste management and alternative material utilization in the construction industry. This study investigates the geotechnical properties of dolomite by-products sourced from Cebu, Philippines, including their compaction behavior, load-bearing capacity, and permeability, to evaluate their suitability in road embankments. Unlike high-grade dolomite, dolomite by-products have not been extensively characterized in existing literature, presenting an untapped opportunity for innovation. This study aims to determine their feasibility as alternative geomaterials by assessing their performance under various geotechnical parameters. The findings of this study seek to provide an innovative solution to waste disposal issues while promoting sustainable construction practices. Identifying positive attributes of this waste material through this study can encourage other researchers to conduct studies on its application as an alternative construction material. By presenting a comprehensive geotechnical characterization of dolomite by-products, this study contributes to sustainable geotechnical engineering and opens new avenues for utilizing mining waste in construction. This will reduce the volume of waste stockpiled at the mining site and help address the disposal problem of dolomite by-products.

A notable contribution of this research is the development of predictive models for key engineering properties, such as hydraulic conductivity as a function of void ratio and load-bearing capacity based on compaction energy. These models offer practical tools for engineers, enabling more precise design decisions for embankment materials. This study fills a critical knowledge gap and advances sustainable geotechnical engineering practices by presenting a comprehensive geotechnical characterization of dolomite by-products. It establishes a pathway for integrating mining waste into construction, offering innovative solutions to waste disposal and resource scarcity issues.

2. Materials and methods

The source of dolomite by-products came from the mining site in Cebu Province. These materials overlying the mineral deposits are discarded after the vital mineral, the high-quality dolomite, is obtained. As shown in Fig. 1, the by-products resemble a typical sand with varying grain sizes. The samples were subjected to laboratory tests following the ASTM standards to determine their geotechnical characteristics. The laboratory tests and their corresponding ASTM standards are summarized in Table 1.

The physical properties of the dolomite by-products, which include the grain-size distribution, Atterberg limits, specific gravity, maximum and minimum index densities, soil classification, microfabric structures, and chemical composition, were determined. The Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) were utilized to identify the dolomite by-products' soil classification. The microstructure and chemical composition of the dolomite by-products were obtained from the Scanning Electron Microscopy (SEM) and the Energy Dispersive X-ray (EDX) tests. The compaction behavior in terms of maximum dry unit weight at optimum moisture content was established using the Standard Proctor test.

Fig. 1 Sample of dolomite by-products

Table 1 Experimental Program

	Test Standards
PRELIMINARY TESTS:	
Grain-size Analysis (Mechanical & Hydrometer method	ASTM D422
Atterberg Limits Test	ASTM 4318
Specific Gravity Test	ASTM D854
Minimum Index Density Test	ASTM D4253
Maximum Index Density Test	ASTM D4254
Standard Proctor Test	ASTM D698
Energy Dispersive X-ray (EDX) Analysis Test	-
Scanning Electron Microscopy (SEM) Test	-
MAIN EXPERIMENTAL PROGRAM:	
California Bearing Ratio (CBR) Test	ASTM D1883
Rigid wall Permeability Test (Constant Head)	ASTM D2434

The California Bearing Ratio (CBR) test, as specified by ASTM D1883, is a penetration test used to evaluate the load-bearing capacity of materials such as dolomite by-products and determine their suitability for road construction. The test measures and compares the bearing capacity of a material with that of a standard crushed stone under controlled laboratory conditions. In this test, the soil sample is compacted into a cylindrical mold with 150 mm diameter and 175 mm height. The compaction process involved applying varying compaction energy levels, represented by the number of blows for every soil layer, using a 4.54 kg rammer. The varying compaction energy simulates the different compaction levels in actual embankment preparation. To replicate field conditions during heavy rainfall or flooding, the compacted sample is soaked in water for 5 days, ensuring it reaches 100% saturation. This step is critical for materials in areas prone to waterlogging or floods, as it allows an accurate assessment of their load-bearing capacity under such conditions. After soaking, the sample is tested in a CBR loading frame, which applies a uniaxial load at a constant rate of 1.27 mm/min. The load required to penetrate the sample with a 49.5 mm diameter piston is recorded at specific penetration intervals to generate a load-penetration curve. The CBR value is calculated as the ratio of the penetration stress required to achieve a penetration depth of 2.54 mm compared to a standard penetration stress of 6.9 MPa or at a penetration depth of 5 mm compared to a standard penetration stress of 10.3 MPa. The higher of the two ratios, expressed as a percentage, is reported as the CBR value. This value is a key parameter for evaluating the material's performance in road construction and other load-bearing applications. Predictive models for CBR values, based on compaction energy and dry unit weight, were formulated to provide practical tools for adapting dolomite by-products to specific geotechnical applications, enhancing their value as a recycled material.

As specified by ASTM D2434, the constant head permeability test was conducted to determine the coefficient of permeability of dolomite by-products and evaluate their suitability as embankment materials. This test provides insight into the material's ability to allow water flow, a critical property for geotechnical and hydraulic applications. The test used a rigid wall permeameter with an internal diameter of 6.33 mm and a sample height of 14 cm. The permeability tests were conducted under constant head conditions with a minimum hydraulic gradient of 4, ensuring a steady and consistent water flow through the sample during the test. A moist tamping method was employed to prepare the test specimens. Reconstituted samples were compacted to achieve initial

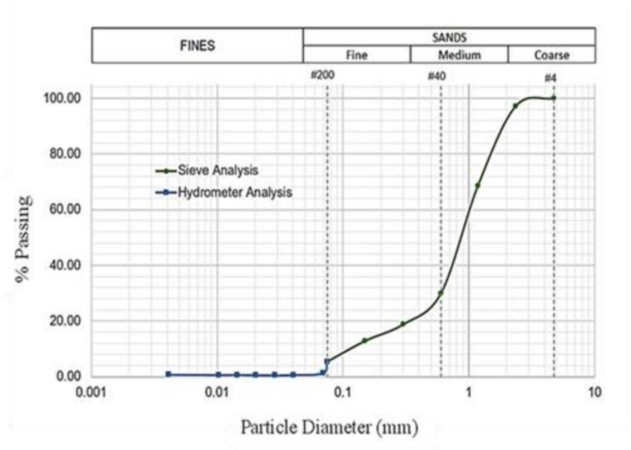

Fig. 2 Grain-size distribution curve of dolomite by-product

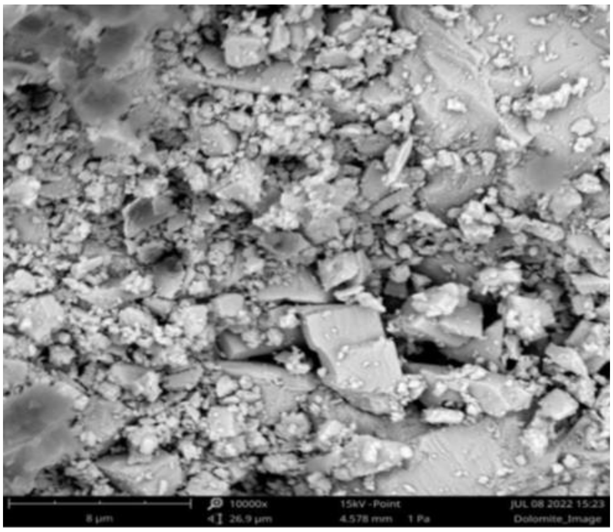

Fig. 3 Micrograph of dolomite by-product at 10,000x magnification

relative compactions of 60%, 70%, 80%, and 90%, allowing the study to explore how varying levels of compaction, and consequently, different void ratios, affect the permeability characteristics of the dolomite by-products. The test results were used to develop a predictive model for the permeability coefficient as a function of the void ratio. This relationship helps assess how changes in the sample's void ratio influence its ability to transmit water. Statistical analysis was performed using a paired-sample T-test to validate the accuracy and predictive capability of the formulated model. This analysis ensured that the predicted permeability values closely matched the measured data, confirming the model's reliability for practical applications.

3. Results and discussion

3.1 Physical properties

The grain-size particles of the dolomite by-products consisted of 3% coarse sand, 67% medium sand, 24% fine sand, and 6% fines. The distribution of particle sizes within a soil mass is represented by a grain-size distribution curve (GSDC) shown in Fig. 2. The GSDC is used to measure the grading characteristics of soil samples in terms of effective size, median size, the uniformity coefficient, and the coefficient of curvature. The effective size, D_{10}, is 0.12mm, while the median size, D_{50}, is 0.85 mm. The uniformity coefficient (Cu) and curvature coefficient (Cc) were computed as 8.78 and 2.72, respectively. Based on the Unified Soil Classification System (USCS), the dolomite by-products are classified as well-graded silty sand with a symbol of SW-SM. According to the AASHTO soil classification system, the by-products belong to group A-1-b, which has an excellent to good general subgrade rating.

The index properties of dolomite by-products are summarized in Table 2. From the Atterberg limits test, the plasticity index (PI) is less than 4, suggesting that dolomite by-products are low-plasticity silts. The specific gravity is 2.84, a typical value for a dolomite mineral, and is slightly higher than the specific gravity of inorganic clay soil. A study by Surendra Roy (2016) proved that an increase in specific gravity led to a rise in the CBR value. A higher value of specific gravity strengthens roads and foundations (Roy 2016).

3.2 Microfabric structure and chemical composition

The microfabric structure of dolomite by-products, as seen in Fig. 3, shows an angular block with relatively sharp angles in most of the particles at varying sizes. The alignment of the particles goes in random directions with minimal to no pore spaces, depicting the compactness of the sample. A well-graded, angular material is commonly desired for its good compaction performance in construction. Its particles tend to bind together, depicting a dense grain packing, resulting in more excellent frictional resistance. The shear strength of soil is derived from the frictional forces as the result of the interlocking of the particles. Soil consisting of coarser grains with varying sizes and angular shapes tends to exhibit greater shearing resistance (Yagis 2001, Li 2013). This suggests that the dolomite by-product is expected to show good strength when used as an embankment material.

The chemical composition of the sample from the energy-dispersive X-ray (EDX) test is presented in Table 3. The dolomite's nature as a carbonate mineral is evident in the results where Oxygen (O) and Carbon (C) are the two most dominant chemical elements. Carbon and oxygen in the sample indicate that they can influence soil stability by stabilizing aggregates (Rowley *et al.* 2018). Previous studies found that the characteristics of carbonate aggregates containing dolomite have potential applications for road surfaces and as embankments. The presence of low Magnesium (Mg) indicates that the sample is a secondary type of dolomite commonly formed in a seawater environment. The sample also contains considerable Nitrogen (N), which is widely found in silicate minerals. Since dolomite is not a silicate mineral, this is not a typical chemical element of dolomite. The disparity of this finding to the original composition of pure dolomite can be attributed to the nature of the sample as a by-product wherein different minerals have already been incorporated into it during its transport or in the

Table 2 Index properties of dolomite by-products

Specific Gravity, Gs	2.84
Liquid Limit, LL (%)	13
Plastic Limit, PL (%)	11
Plasticity Index, PI (%)	2
Maximum Void Ratio, e_{max}	0.832
Minimum Void Ratio. e_{min}	0.429
Maximum Dry Unit Weight, γ_{dmax} (KN/m^3)	18.31
Optimum Moisture Content, OMC (%)	8.34

Table 3 Chemical composition of dolomite by-products

Element	Weight concentration (%)
Oxygen	41.89
Carbon	16.79
Calcium	9.99
Nitrogen	23.73
Magnesium	7.59

stockpile at the mining site. The chemical composition of dolomite by-products indicates its suitability for construction purposes, particularly in the aspect of hydration that can influence soil stability.

3.3 Compaction behavior

In roadway construction, subgrade materials must be compacted to increase their unit weights, which enhances the load-bearing capacity of the structures built over them (Das 2018). Compaction improves the strength characteristics of soils by reducing their void ratio, thereby increasing the soil's density and stability. The degree of compaction is commonly expressed in terms of dry unit weight, γ_d. During the compaction process, water is added to the soil to act as a lubricant, facilitating the sliding of soil particles into a denser configuration. For a given compaction effort, there exists an optimum moisture (w_{opt}) at which the soil achieves its maximum dry unit weight (γ_{dmax})

To evaluate the compaction behavior of dolomite by-products, a standard Proctor test was performed, and the compaction curve was derived from the test results as shown in Fig. 4. The results indicate that the dolomite by-products achieved a maximum dry unit weight (γ_{dmax}) of 18.31 kN/m³ at an optimum moisture content (w_{opt}) of 8.34%. This suggests that the dolomite material compacts efficiently with relatively low moisture content compared to typical granular subgrade materials, which often require higher moisture levels for optimum compaction. A comparative analysis with typical compaction values for other subgrade materials, shown in Table 4, was conducted to assess the suitability of dolomite by-products as subgrade materials. Granular soils, such as sandy and gravelly, typically exhibit maximum dry unit weights ranging from 16 to 20 kN/m³, with optimum moisture contents between 7% and 15% (Das 2018, Holtz 2011). The maximum dry unit weight and optimum moisture content of dolomite by-product align well within this range, confirming their suitability as a subgrade material. The angularity of the particles, as observed in the microstructure (Fig. 3), likely contributes to their good compaction characteristics, as angular particles interlock more effectively during compaction compared to rounded particles.

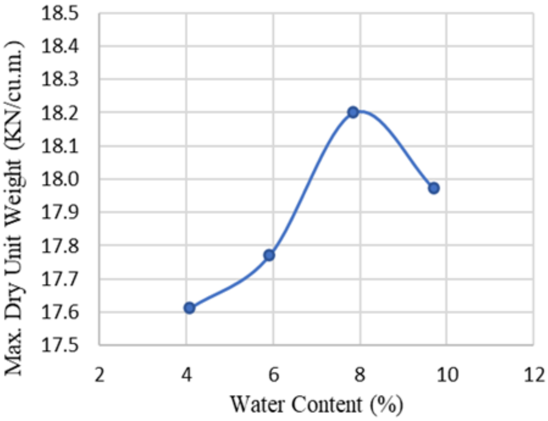

Fig. 4 Compaction curve of dolomite by-product

Table 4 Typical compaction properties of subgrade materials

Subgrade Materials	γ_{dmax} (kN/m^3)	w_{opt} %
Granular subgrades (Das 2018, Holtz *et al*. 2011)	16 to 20	7 to 15
Clayey subgrades (Bowles 1996)	13 to 18	12 to 25
Dolomite by-products (this study)	18.31	8.34

Table 5 Compaction characteristics of dolomite by-products

Max. dry unit weight, γ_{dmax} (kN/m^3)	18.31
Optimum moisture content, w_{opt} (%)	8.34
Compaction Characteristics and Rating of USCS Classes for Soil Construction (US Army Corp of Engineers, 1953)	
Compaction Characteristics	Good
Compressibility and Expansion	Almost none to slight
Value as Embankment Material	Very stable to reasonably stable when dense
Value as Subgrade Material	Good to fair
Value as Base Course	Fair to poor
General Guide to Selection of Soils based on Anticipated Embankment Performance as per AASHTO Classification (Krebs *et al*. 1971)	
Anticipated Embankment Performance	Excellent to good

The compaction characteristics and ratings of dolomite by-products were evaluated based on the Unified Soil Classification System (USCS) and the AASHTO classification criteria presented in Table 5. The dolomite by-product exhibits good compaction characteristics, with compressibility and expansion potential rated as almost

Table 6 Soil rating for roads (adopted from Bowles 1992)

CBR value	General Rating	Uses
0 - 3	Very poor	Subgrade
3 – 7	Poor to fair	Subgrade
7 - 20	Fair	Subbase
20 - 50	Good	Base, Subbase
> 50	Excellent	Base

Table 7 CBR values of dolomite by-products

Compaction Energy	Dry Unit Weight (KNm^3)	CBR value	Rating	Uses
10 blows	15.35	6	Poor to fair	Subgrade
20 blows	16.45	8	Faie	Subgrade
30 blows	17.49	11	Fair	Subgrade
45 blows	17.90	15	Fair	Subbase
56 blows	18.25	17	Fair	Subbase
65 blows	18.36	19	Fair	Subbase

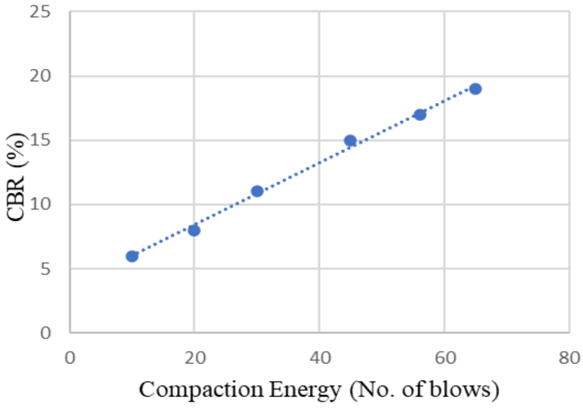

Fig. 5 CBR value against compaction energy

none to slight. This indicates that the material has a low potential for settlement or swelling. Furthermore, the dolomite material is rated as very stable to reasonably stable when dense for use as embankment material. This proves that the material is highly reliable for long-term stability. Its performance as subgrade material is rated good to fair, while its use as a base course is rated fair to poor. Dolomite by-products can perform adequately as a subgrade material under moderate to high load conditions but with limited performance as a base course under heavy repeated loads and may require supplementary stabilization. The compaction test results suggest that the dolomite by-products demonstrate compaction properties comparable to high-performing granular materials. Additionally, their low compressibility and high stability ratings suggest excellent performance in embankment and subgrade applications, where settlement and deformation control are essential.

3.4 Load-bearing capacity

The California Bearing Ratio (CBR) test is commonly used to assess the strength of a subgrade soil, subbase, and base course material for use in road and airfield pavements. The required thickness of pavements is determined empirically based on the CBR value. The CBR tests assessed the load-bearing capacity of the dolomite by-products under varying compaction energies, represented by the number of blows applied during compaction. This study conducted the CBR test by subjecting the dolomite by-products to 10, 20, 30, 45, 56, and 65 blows to create a sample at varying unit weights.

Results from the CBR test indicate the load-bearing rating of the dolomite by-products using the criteria adopted from Bowles (1992), as seen in Table 6.

The test results for each number of blows and its rating as embankment material for roads are shown in Table 7. The test results show that the CBR value is directly proportional to the amount of compaction energy applied. This proves that the performance of the dolomite byproducts as a material for road construction improves when subjected to more compaction energy. As the compaction energy increases, the dry unit weight increases, and the CBR value increases. It is expected that the load-bearing capacity of the soil is affected by the in-situ density of the soil. The soil particles are densely packed at greater unit weights, resulting in greater load-carrying capacity. The dolomite by-product has a rating of fair as embankment material at greater compaction energy.

A graph showing the CBR against the number of blows was plotted and shown in Fig. 5. It is evident from the graph that there is a linear relationship between the CBR value and the applied compaction energy. A linear equation was generated through regression analysis that can determine the value of CBR as a function of a given number of blows and is presented in Eq. (1). The fitted model shows a strong linear correlation, with a coefficient of determination, $R^2 = 0.99$. The linear relationship indicates that the CBR value improves predictably as compaction energy increases. This provides confidence in the material's performance under controlled compaction conditions. The equation allows engineers to determine whether the dolomite by-product can achieve sufficient load-bearing capacity under specific compaction conditions, essential for its use as a subbase material.

$$\mathrm{CBR} = 0.242x + 3.565 \tag{1}$$

Where: x = number of blows corresponding to compaction energy.

It is a common practice in engineering construction that a CBR value of 56 blows is used to assess the suitability of the soil for its intended use. Using Eq. (1), the CBR value for the standard compaction energy of 56 blows was estimated to be 17%, consistent with test results. For this CBR value, the dolomite by-product is suitable for use as subbase material with a general rating of fair.

It is always desirable that the embankment materials are compacted at a maximum dry unit weight to achieve higher bearing capacity and reduce the susceptibility to settlement. To assess the load-bearing capacity of a dolomite by-product in relation to its dry unit weight, the CBR values are plotted against the dry unit weight, as shown in Fig. 6. The relationship between the CBR and the dry unit weight is

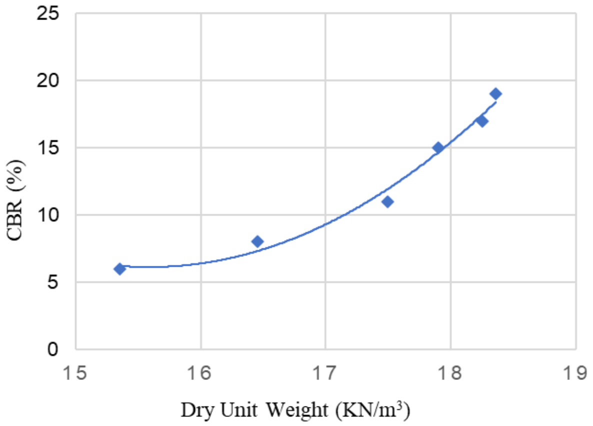

Fig. 6 CBR value against the dry unit weight of dolomite by-products

nonlinear. It is represented by Eq. (2) with a coefficient of determination, $R^2 = 0.98$. The high R^2 value supports its reliability for practical design applications. This nonlinear equation highlights the relationship between CBR and dry unit weight, showing that higher dry unit weights, achieved through better compaction, increase CBR values.

$$\mathrm{CBR} = 1.605x^2 - 50.06x + 396.36 \tag{2}$$

Where: x = dry unit weight in $\mathrm{KN/m^3}$

The developed predictive model is useful in construction applications where the desired CBR rating can be attained by getting the corresponding in-situ dry unit weight of dolomite by-products or vice versa. Knowing the achievable in-situ dry unit weight allows designers to predict the material's performance without extensive additional field tests. According to Schaefer *et al.* (2008), a CBR value of at least 10 is needed to develop a subgrade for highway engineering because a value less than 10 will deflect the subbase material under traffic loadings and cause pavement deterioration. Using Eq. (2) the CBR value at maximum dry density is 17.8%, which can be rated as fair and suitable as a subbase. This proves that the dolomite by-products are viable to use as a material for road construction.

The predictive models, Eqs. (1) and (2), reduce the need for extensive field trials by enabling accurate predictions based on controlled laboratory conditions. This can guide the efficient use of dolomite by-products by predicting their behavior under varying compaction scenarios, ensuring that the material meets the required performance criteria for road construction. By providing reliable performance metrics, the predictive models support the integration of waste materials into engineering applications, promoting sustainability in construction practices.

3.5 Permeability characteristics

The permeability test was performed using a rigid wall permeameter mold on specimens with four (4) different relative compactions (Rc), namely, 60%, 70%, 80%, and 90%. This is to simulate the possible required relative compaction on site. The coefficient of permeability (k) was calculated using Darcy's Law, and the results for each relative compaction are presented in Table 8. The measured values of k range from 0.0187 to 0.0417 cm/sec. The dolomite by-product can be classified as exhibiting medium permeability, which is typical for fine sand. In road construction, subgrade materials with good drainage capacity are recommended. (Edora and Adajar 2021).

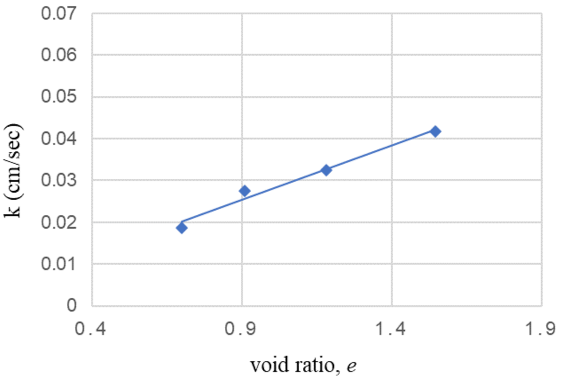

Fig. 7 Coefficient of permeability, k vs. void ratio

Table 8 Coefficient of permeability (k) for each void ratio (e)

Relative Compaction, Rc	Void ratio, e	k measured (cm/sec)
60%	1.545	0.0417
70%	1.181	0.0325
80%	0.909	0.0275
90%	0.697	0.0187

Various factors influence the coefficient of permeability of soils. Several authors have correlated the coefficient of permeability with geotechnical parameters for various types of soil to identify the soil parameters that significantly affect the k values. The study of Oren *et al.* (2018) correlates the coefficient of permeability with clay content, liquid limit, and plasticity index of geosynthetic clay liners. The effect of microstructure on the permeability characteristics of saturated clays has been studied by Chen *et al.* (2019), and it was proven that the void ratio is the suitable soil parameter to represent the effect of soil fabric on the permeability characteristics of saturated soft clays. A modified Kozeny-Carman equation using the effective void ratio and the specific surface area was used to predict the permeability coefficient of remolded loess samples (Hong *et al.* 2020). The empirical model for predicting the coefficient of permeability of non-plastic fine tailing takes into consideration the effect of void ratio and fine contents (Adajar and Zarco 2014). It can be noted from the various correlations that the permeability characteristic of soil is related to its void ratio. As stated by Powrie (2018), the permeability characteristic of soils is significantly affected by the void size, which is associated with the particle size of the soil.

In this study, the relative compaction is expressed in terms of the void ratio to formulate a model that can predict the permeability coefficient of dolomite by-products as a function of the in-situ void ratio. Fig. 7 shows the values of the coefficient of permeability k at the different void ratios corresponding to the relative compaction. Test results showed that k is proportional to the void ratio, e. The relationship between the coefficient of permeability and the void ratio can be represented by Eq. (3) with a coefficient of determination, $R^2 = 0.98$. As the coefficient of determination is near the value of 1, this indicates that the developed predictive model fits the data well.

$$k = 0.026e + 0.002 \tag{3}$$

Where:
k = coefficient of permeability in cm/sec
e = void ratio

To validate the predictive capability of the developed model, the k values calculated using the predictive model Eq. (3) were compared with the measured values from experimentation. A statistical analysis using a T-test for paired samples was done to determine if there was any significant difference between the measured and predicted values. The null hypothesis for this test states that there is no significant difference between the measured and predicted values of k using Eq. (3) at a significance level of 0.05 ($\alpha = 0.05$). Table 9 presents the results from the statistical analysis. The results of the statistical analysis show a t_{Stat} (0.498) less than t_{Critical} (2.353) and a p-value (0.327) greater than 0.05. This means that the null hypothesis is true. Thus, it can be said that there is no significant difference between the measured and predicted k values using Eq. (3).

The strength of association between the measured and predicted k was verified through Pearson's correlation coefficient, and the data are presented in the scatter plot as shown in Fig. 8. The scatter of the data points is noticeably near the equality line, indicating a positive linear correlation between the measured and predicted k. The Pearson correlation coefficient is 0.91, which means a very strong relationship between the two variables involved, the measured and predicted k, according to the guide established by Evans (1996). As such, it can be concluded that the proposed predictive model, Eq. (3), can be used to predict the coefficient of permeability, k of dolomite by-products as a function of void ratio. The proposed equation applies to dolomite by-products with low plasticity. However, as the model considers only the void ratio in its formulation, considering other factors, such as particle size and shape, may yield different values of k. Despite the mentioned limitations, the proposed model is a valuable tool for predicting the coefficient of permeability of soil with geotechnical characteristics similar to the dolomite by-products in this study. It may be used to obtain initial ideas and estimations when representative data is unavailable.

Table 9 Paired T-test results comparing measured and predicted k values

	k Measured	k Predicted
Mean	0.031310167	0.03023016
Variance	0.000096748	0.000102167
Observations	4	4
Pearson Correlations	0.905828212	
Hypothesized Mean Difference	0	
Df	3	
t Stat	0.498182922	
P(T<=t) one-tail	0.326293375	
T Critical one-tail	2.353363435	
P(T<=t) two-tail	0.652586749	
T Critical two-tail	3.182446305	

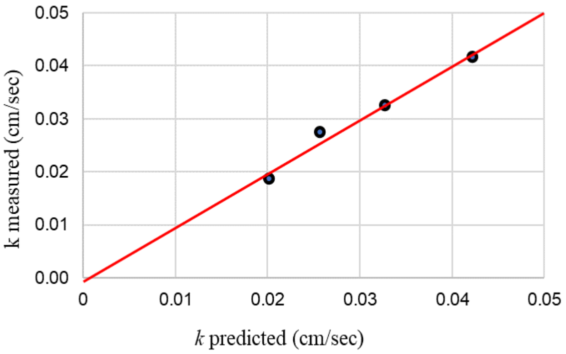

Fig. 8 Measured vs. predicted k values

3.6 Comparative analysis with traditional subgrade materials

To assess the performance of dolomite by-products, their geotechnical properties were compared with traditional subgrade materials such as sandy, gravelly, and clayey soils. The values are derived from established geotechnical references. Table 10 summarizes the key parameters.

The results show that the dolomite by-products exhibit geotechnical properties comparable to sandy subgrades and outperform clayey subgrades in dry unit weight, load-bearing capacity, and permeability. However, they fall short of the higher CBR values observed in gravelly subgrades. The medium degree of permeability of dolomite by-products ensures adequate drainage, a property beneficial for subbase and subgrade applications in road construction.

This comparative analysis demonstrates the potential of dolomite by-products as a viable alternative to traditional subgrade materials, particularly in projects where sustainable waste management and material reuse are priorities.

4. Conclusions

This study provides a comprehensive geotechnical characterization of dolomite by-products from Cebu Province, Philippines, and evaluates their suitability as alternative geomaterials for road embankments. The following conclusions are drawn:

- The dolomite byproduct is classified as well-graded silty sand with low-plasticity silts denoted by USCS symbol SW-SM. It falls under the AASHTO group A-1-b, indicating an excellent to good general subgrade rating. Microfabric analysis revealed angular particles with sharp edges, promoting strong interlocking and stability. Dominant chemical elements

Table 10 Comparative analysis with traditional subgrade materials

Material Type	Dry Unit Weight (kN/m^3)	Optimum Moisture Content (%)	CBR Value (%)	Coefficient of Permeability, *k* (cm/sec)	Source
Sandy subgrades	16 to 20	7 to 15	10 to 50	0.01 to 0.1	Das (2018), Bowles (1996)
Gravelly subgrades	18 to 22	5 to 10	30 to 80	0.001 to 0.01	Schaefer *et al.* (2008), Krebs and Walker (1971)
Clayey subgrades	13 to 18	12 to 25	2 to 10	0.0001 to 0.001	Holtz *et al.* (2011)
Dolomite by-products	18.31	8.34	6 to 19	0.0187 to 0.0417	This study

included Oxygen and Carbon, typical of carbonate minerals, along with traces of Magnesium, Calcium, and an atypical presence of Nitrogen due to environmental mixing.

- With a dry unit weight of 18.31 kN/m^3 at an optimum moisture content of 8.34%, the dolomite by-product demonstrates good compaction characteristics. It is rated as very stable to reasonably stable for embankment applications, with anticipated performance classified as excellent to good. This stability underscores its reliability for long-term infrastructure applications.
- The load-bearing capacity was assessed through the CBR value. The CBR values ranged from 6% to 19%, improving performance proportionally to compaction energy. At maximum dry density, the CBR value of 17.8% confirms the material's suitability as a fair-rated subbase. The relationship between the CBR value and the dry unit weight is nonlinear and directly proportional, which exhibits that as the dry unit weight increases, the CBR value also increases. Predictive models for CBR values, based on compaction energy and dry unit weight, showed strong correlations, offering practical tools for field applications.
- The permeability coefficient ranged from 0.0187 to 0.0417 cm/sec, indicating medium permeability suitable for subgrade applications with adequate drainage. The values of the coefficient of permeability gradually increase as the void ratio increases. A reliable predictive model for permeability as a function of void ratio was developed and validated, enabling practical design applications.
- Dolomite by-products exhibit comparable geotechnical properties to sandy subgrades, surpassing clayey subgrades in dry unit weight, load-bearing capacity, and permeability. While they do not match the higher CBR values of gravelly subgrades, their medium permeability and sustainability benefits make them a viable alternative for subgrade and subbase applications.
- By repurposing mining waste, this study contributes to sustainable geotechnical practices and promotes resource-efficient infrastructure development. Integrating dolomite by-products into construction addresses waste disposal issues while reducing the reliance on natural materials.

The study's limitations include the lack of data on shear strength and compressibility, which are critical for a more holistic assessment of the material's performance. Future studies should investigate these properties and consider the long-term behavior of dolomite by-products under cyclic loading and environmental conditions. Exploring stabilization techniques and blending with other materials may enhance their suitability and performance.

This research underscores the potential of dolomite by-products as sustainable alternatives in geotechnical applications, fostering innovation and environmental stewardship in the construction industry.

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