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Strength evaluation of limestone powder waste stabilized with cement using the needle penetration test

Jose Luis Pastor, Erick Gutierrez, Miguel Cano
Department of Civil Engineering, University of Alicante, Alicante, Spain, joseluis.pastor@ua.es

Ryohei Ishikura
Department of Civil Engineering, Kyushu University, Japan

ABSTRACT: The natural stone industry generates limestone powder waste during the polishing and cutting processes. This by-product could be used in earthworks as a new material with a low ecological footprint. Strength evaluation is usually performed using the unconfined compressive strength (UCS) test for general geotechnical soil characterization or the California Bearing Ratio (CBR) test when the soil is used for embankments or pavement layers in transportation geotechnics. In this research, the strength of limestone powder waste stabilized with 2%, 4%, 6% and 8% Portland cement (by dry soil weight) was studied using the needle penetration test (NPT), UCS and CBR tests. Although NPT is commonly used for other applications, such as jet grouting or weak rocks, it is not commonly used for soil stabilization. The results obtained from these samples showed a linear increase in the UCS and Needle Penetration Index (NPI) as the cement content increased up to 8%, yielding a good linear fit between UCS and NPI. The CBR results show an increase in the value obtained as cement content increases. The needle penetration test was performed on these samples after mixing the limestone powder waste with the cement, after 7 days of curing in a wet chamber, and after an additional 4 days of submersion in water. The results show no difference in the NPI after mixing, as the cement did not have enough time to react with water, and a general linear trend in the NPI as the cement content increases, both after 7 days of curing and after an additional 4 days of submersion. The correlation between CBR and NPI seems to fit a logarithmic trend. The results indicate the possibility of determining the strength of limestone powder waste stabilized with cement with a reasonable degree of confidence.

KEYWORDS: Needle penetration test, limestone powder waste, unconfined compressive strength, CBR.

1 INTRODUCTION

The significant environmental impact of earthworks—such as embankments—due to the large volumes of soil required for their construction has led to growing interest in alternative materials, particularly industrial by-products. Among these, limestone powder waste (LPW) has emerged as a promising material for soil stabilization. LPW is a by-product generated during the cutting and polishing activities in the natural stone industry. During the manufacturing processes in an ornamental stone production facility, a fine calcareous powder is produced as a by-product, which is currently treated as waste and disposed of in landfills. Although LPW is an inert by-product, landfill disposal still poses a considerable environmental impact. Several researchers have investigated the effect of this industrial waste on soil stabilization. Cabalar and Omar (2023) reported an increase in the strength properties of a clayey soil when it was mixed with up to 30% LPW. This valuable effect was observed in the Unconfined Compressive Strength (UCS) test, and especially in the California Bearing Ratio (CBR), where the value obtained increased up to 5.3 times when adding the by-product in comparison to the natural soil result. Other positive effects such as a reduction in deformability and in the free swelling of the clayey soil were also observed. Similar results were obtained by other researchers when using this by-product for clayey soil stabilization. Sabat and Muni (2015) also reported an increase in the UCS and CBR results after adding LPW. Similar results -increased strength, reduced deformability, and lower swelling index- were obtained by other researchers (Brooks et al., 2011; Pastor et al., 2019; Deboucha et al., 2020).

LPW has also been investigated for use as a ternary element with soil and commercial binders such as lime or cement. Hammad, Mohamedzein and Al-Aghbari (2024) obtained an increase in the UCS of a low plasticity clayey soil stabilized with cement when marble powder was used to replace up to 30% of the binder. A slight increase in UCS was reported by Kufre Etim et al. (2021) when 8% of limestone quarry dust was added to a low plasticity soil stabilized with 8% of cement. Wang et al. (2018) and Jiang et al. (2020) stated that a refinement in the pore structure of cementitious materials occurred when fine limestone powder was added.

Recently, the possibility of using LPW not only as an additive, but also as a standalone material for embankment construction was investigated (Pastor et al., 2025). The results showed that LPW can be used for embankment construction fulfilling the Spanish requirements for inner layers of embankments. This option would allow us to employ large amounts of by-product for each project. LPW strength could be improved by adding lime or cement. In this research, the effect of adding 2%, 4%, 6%, and 8% Portland cement (by dry soil weight) to LPW was investigated. Strength was obtained by two well-known tests in transportation geotechnics, CBR and UCS, and with the Needle Penetration Test (NPT). Obtaining a correlation between NPT and CBR and UCS results would make it possible to increase the number of tests performed on this material, reducing the time and cost of strength determination and enabling in situ assessment in the field.

2 MATERIALS

2.1 *Limestone powder waste*

The limestone powder waste (LPW) used in this research was obtained from a temporary dumpsite from a natural stone factory located in Alicante province (Spain). One hundred percent of the sample passed through the 0.08 mm sieve. The Liquid Limit was 22.8, the Plastic Limit was 18.6, and the Plasticity Index was 4.2. Therefore, it can be classified as a low plasticity silt according to the Unified Soil Classification System (USCS). A semiquantitative X-ray diffraction analysis was performed, revealing that 68% of the sample was calcite and 26% was dolomite; the remainder consisted of mineral phases present in minor amounts.

2.2 *Cement*

A pozzolanic cement designated as CEM IV/B 32.5 N-SR was used for the stabilization of the limestone powder. The cement has a strength class of 32.5 MPa, with normal strength development and sulphate resistance.

3 METHODS

3.1 *Needle Penetration Test*

The Needle Penetration Test (NPT) was used to determine the Needle Penetration Index (NPI) according to the method suggested by the International Society of Rock Mechanics (Ulusay et al., 2014). The equipment used was a needle penetrometer with a strengthened steel needle of 0.84 mm diameter, manufactured by Maruto Corporation. The NPI (N/mm) for each sample was determined as the mean value of 10 measurements, using the following equations:

- When $P = 100$ N and $d_a \leq 10$ mm:

$$NPI = \frac{100}{d_a} \tag{1}$$

- When $d_a = 10$ mm and $P \leq 100$ N:

$$NPI = \frac{P}{10} \tag{2}$$

Where P is the applied force in newtons (N), and d_a is the needle penetration depth in millimeters (mm).

The NPI was obtained in two types of samples: a) samples in CBR molds, 152.5 mm in diameter and 177.8 mm in height, compacted to 25%, 50% and 100% of the Modified Proctor energy; and b) samples with the same dimensions as those used in the UCS tests, 50 mm in diameter and 100 mm in height, compacted using energy equivalent to the Standard Proctor Test. The use of two different compaction energies for the NPT was intended to allow comparison with the CBR and UCS results.

3.2 *Unconfined Compressive Strength*

The Unconfined Compressive Strength (UCS) was determined as the maximum compressive strength obtained during the test. The test continued until a peak value was obtained, or a maximum deformation of 15% of the initial vertical height was reached. Samples, 100 mm height and 50 mm diameter, were compacted using equivalent energy to the Standard Proctor Test. The loading rate was 1 mm per minute, corresponding to 1% of the sample height. Tests were performed according to the standard ASTM D2166-M (ASTM International, 2016). The UCS values were calculated as the average of three tests.

3.3 *California Bearing Ratio*

The California Bearing Ratio (CBR) index was obtained according to the standard ASTM D1883-21 (ASTM International, 2021). Three specimens were used for each test, each with different degrees of compaction: one compacted to 100% of the Modified Proctor Test (D_c = 100%), another to 50% (D_c = 50%), and the third to 25% (D_c = 25%). After preparation, the samples were stored in a humidity chamber for 7 days, then submerged in water for 4 days, and finally tested. The specimens were 152.5 mm in diameter and 177.8 mm in height.

3.4 *Experimental setup*

The experimental setup involved sample preparation using limestone powder waste and 0%, 2%, 4%, 6% and 8% cement. The dry components were blended before the addition of distilled water to achieve the optimum moisture content determined by Proctor tests. After demolding, the specimens were sealed in plastic bags and stored for 7 days in a controlled chamber at 20 ± 2 °C and a relative humidity above 90%.

4 RESULTS AND DISCUSSION

4.1 *Needle Penetration Test*

The NPI of the samples in CBR molds was calculated at three different stages: after mixing, after 7 days in a humidity chamber, and finally, after an additional 4 days submerged in water. The NPI obtained immediately after sample compaction is shown in Figure 1. The NPI increases with higher degrees of compaction. However, NPI does not show variation with the percentage of cement for the three degrees of compaction. This is likely due to insufficient time for the cement for setting and hardening. The effect of increasing the percentage of cement can be observed after 7 days of curing in the humidity chamber. Figure 2 shows the NPI of these samples. It can be observed that the general trend for the three degrees of compaction is an increase in the NPI as the binder percentage increases. A general trend is also observed for the NPI to increase with the degree of compaction. Finally, the results for the samples tested after 7 days in the humidity chamber and an additional 4 days submerged in water are shown in Figure 3. These results confirm the same trend of higher NPI as cement percentage increases, and higher NPI for higher degrees of compaction. Some drops have been observed for 8% cement content, which have been considered outliers.

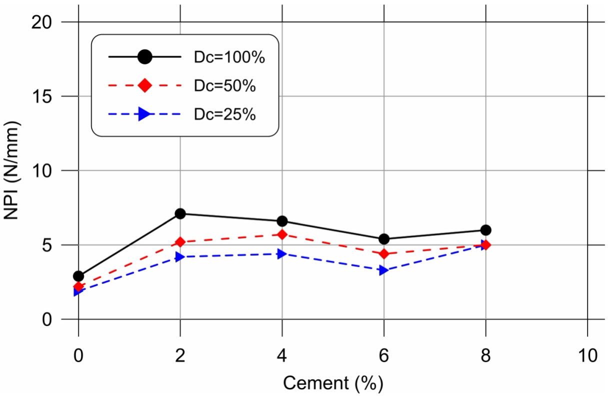

Figure 1. NPI after compaction of samples with a degree of compaction equal to 25%, 50%, and 100%.

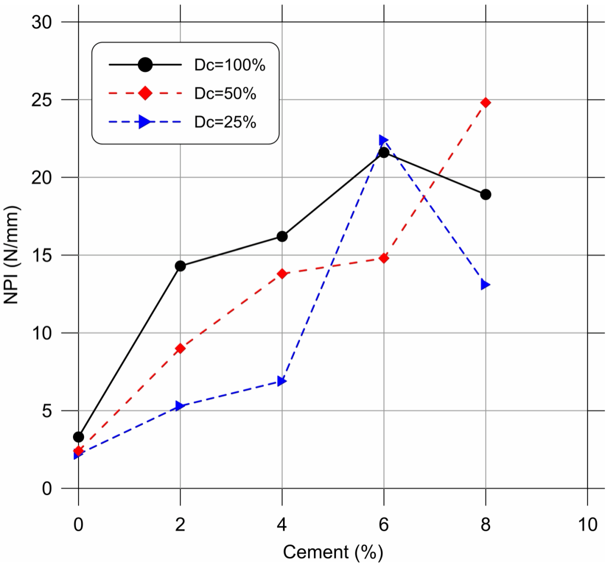

Figure 2. NPI after 7 days in the humidity chamber of samples with a degree of compaction equal to 25%, 50%, and 100%.

The NPI of the samples with the same dimensions as those used in the UCS test was calculated after 7 days in the curing chamber. The results of these samples are shown in Figure 4. As can be seen in this figure, the NPI increases as the percentage of cement increases, showing an approximately linear trend.

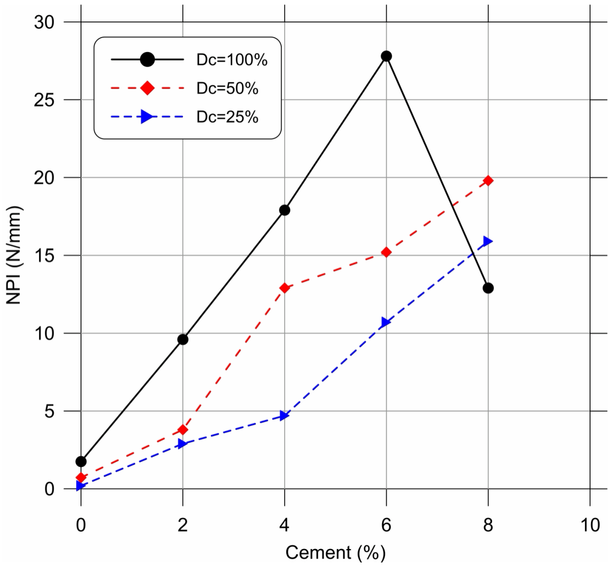

Figure 3. NPI after 7 days in the humidity chamber and 4 days submerged of samples with a degree of compaction equal to 25%, 50%, and 100%.

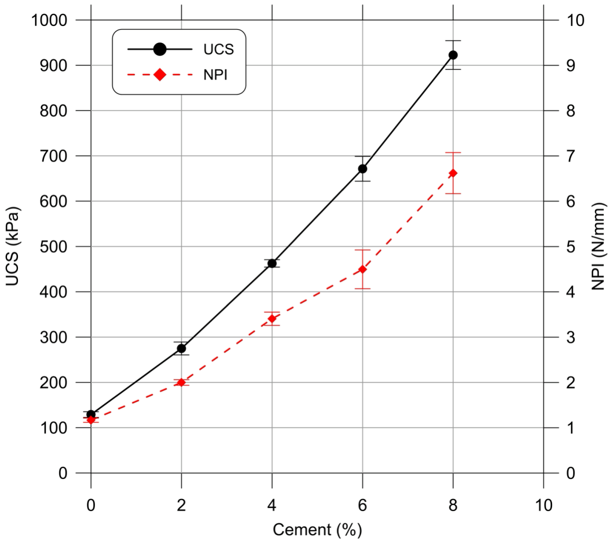

Figure 4. UCS and NPI of samples compacted using equivalent energy to Standard Penetration Test with different percentages of cement.

4.2 *Unconfined Compressive Strength*

The results of the UCS test are shown in Figure 4. An increasing trend in UCS with increasing cement content can clearly be observed. As for the NPI, the UCS seems to follow a linear increasing trend when adding cement to the limestone powder waste.

4.3 *California Bearing Ratio*

The CBR index was calculated for samples with a degree of compaction of 25%, 50% and 100% of the Modified Proctor. The results are shown in Figure 5. The CBR index for samples with a 25% degree of compaction shows a linear increase with the cement content up to the maximum content of 8%. However, the samples with a 50 and 100% degree of compaction showed an asymptotic trend in the CBR index as the cement content increased.

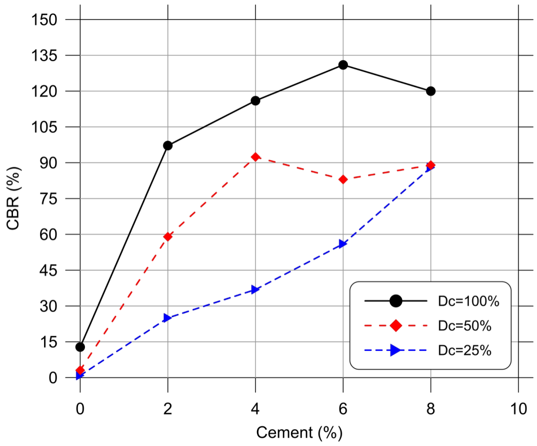

Figure 5. CBR results of samples with a degree of compaction equal to 25%, 50%, and 100%.

5 DISCUSSION

Similar trends were observed for the individual UCS, NPI and CBR results; therefore, a correlation between these parameters is expected. However, some differences were observed between them. The general trend observed for the UCS and NPI results shows an overall increase in strength as the percentage of cement increases, except for the NPI values obtained immediately after sample compaction, where no change in strength was detected with varying cement content for the three degrees of compaction. This is likely due to insufficient time for cement hydration and pore structure refinement. Nevertheless, the CBR results show a linear trend for a degree of compaction of 25%, and an asymptotic trend for compaction degrees of 50% and 100%. The asymptotic trend could be explained by the fact that strength of the mixed soil increases as cement content increases up to a certain value, remaining constant after that point, or even decreasing.

The correlation between CBR and NPI for samples with degrees of compaction of 25%, 50%, and 100% of the Modified Proctor energy can be observed in Figure 6. Values for samples with 25% compaction suggest a linear fit. Nevertheless, the values for 50 and 100% compaction suggest a logarithmic fit, as the CBR index appears nearly asymptotic, or at least exhibits a small slope, beyond a certain NPI value. Although both tests are penetration tests, the difference in the size of the penetration device could explain this trend, as the CBR plunger is 50 mm in diameter, while the needle is only 0.84 mm. This trend was also observed for the individual results of CBR tests. Equations (3), (4), and (5) show the correlation between CBR and NPI for 25%, 50%, and 100% compaction, respectively. Finally, Equation (6) shows the correlation between these indices for all the samples.

- Degree of compaction = 100%

$$CBR = 44.24 \cdot \ln NPI - 7.14 \qquad (R^2 = 0.963) \qquad (3)$$

- Degree of compaction = 50%

$$CBR = 26.49 \cdot \ln NPI + 16.19 \qquad (R^2 = 0.961) \qquad (4)$$

- Degree of compaction = 25%

$$CBR = 17.26 \cdot \ln NPI + 20.17 \qquad (R^2 = 0.818) \qquad (5)$$

- All samples

$$CBR = 27.88 \cdot \ln NPI + 17.17 \qquad (R^2 = 0.795) \qquad (6)$$

Correlations for 50% and 100% compaction show a robust logarithmic fit, with R2 values of 0.961 and 0.963, respectively. The 25% values show a better linear fit, although the logarithmic fit was used for consistency. Finally, the correlation obtained for all samples, regardless of the degree of compaction, had an R2 value of 0.795.

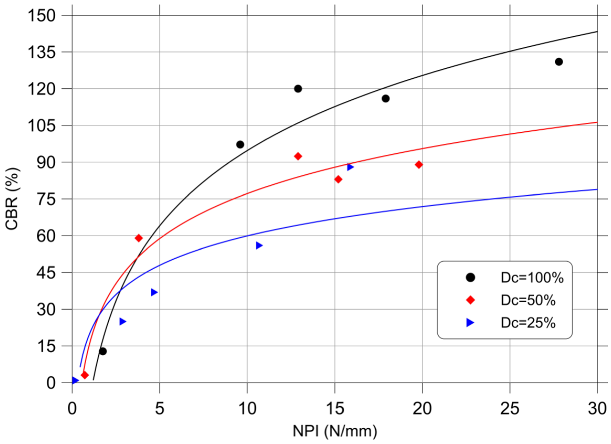

Figure 6. Correlation between California Bearing Ratio (CBR) index and Needle Penetration Index (NPI) samples with a degree of compaction equal to 25%, 50%, and 100% of the Modified Proctor energy.

Figure 7 shows the correlation between UCS and NPI. A clear linear relationship is observed in this figure. Equation (7) represents this linear relationship, assuming the fit line passes through the origin. As seen in the equation, the R^2 value is close to 1, which implies a strong correlation between UCS and NPI.

$$UCS = 141.28 \cdot NPI \qquad (R^2 = 0.998) \qquad (7)$$

Where UCS is the Unconfined Compressive Strength in kPa, and NPI the Needle Penetration Index in N/mm.

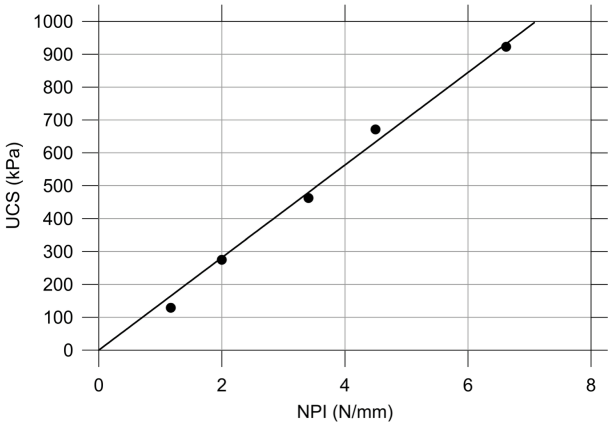

Figure 7. Correlation between Unconfined Compressive Strength (UCS) and Needle Penetration Index (NPI).

6 CONCLUSIONS

The influence of cement addition up to 8% on the strength of limestone powder waste (LPW) for earthworks has been studied using two standard methods (CBR and UCS), and an alternative method, the Needle Penetration Test (NPT). The results show that the strength of LPW can be significantly improved with cement. Strong correlations were obtained between the Needle Penetration Index (NPI) and both CBR and UCS. These correlations suggest that NPI can be used to evaluate the strength of this by-product, reducing the time and cost of strength determination and enabling in situ assessment in the field.

This research compares results of samples compacted with the same water content and compaction energy, and under the same test conditions. The in-situ conditions of the embankment, such as moisture content, sample heterogeneity, and field variability, during the performance of the NPT or any other test, will influence the results obtained. Therefore, this aspect must be considered when interpreting the in-situ test results.

7 ACKNOWLEDGEMENTS

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