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Statistical inferences from a database of lime and cement modified soil in earthworks for residential construction in the UK

Inférences statistiques à partir d'une base de données de sols modifiés à la chaux et au ciment dans les travaux de terrassement destinés à la construction résidentielle au Royaume-Uni

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ABSTRACT: Use of lime for soil moisture conditioning is frequently used for the treatment of soils significantly wet of optimum in order to achieve density-driven specifications for cohesive materials. In a similar fashion, cement is frequently used for the treatment of soil of lower clay content to improve strength overall. This paper presents an assessment for a comparably large database of routine compaction testing across varying soil types in the UK where lime and/or cement has been used in ground improvement for the preparation of structural upfill specifically in residential construction projects. Statistical inferences are drawn from the data and presented for guidance for refinement of design approaches in such projects. It is concluded that the techniques produce a highly reliable structural upfill in terms of relative compaction and percentage air voids.

RÉSUMÉ: L'utilisation de la chaux pour le traitement de l'humidité des sols est fréquemment utilisée pour le traitement des sols fortement mouillés ou optimaux afin de respecter les spécifications de densité des matériaux cohésifs. De manière similaire, le ciment est fréquemment utilisé pour le traitement des sols à faible teneur en argile afin d'améliorer la résistance générale. Ce document présente une base de données de grande taille comparant les tests de compactage de routine effectués sur différents types de sols au Royaume-Uni, où de la chaux et / ou du ciment ont été utilisés pour améliorer les sols et préparer les travaux d'ajustement structurels dans les projets de construction résidentielle. Les inférences statistiques sont tirées des données et présentées à titre indicatif pour affiner les approches de conception dans de tels projets. Nous concluons que les techniques produisent un remplissage structurel extrêmement fiable en termes de compactage relatif et de pourcentage de vides d'air.

Keywords: earthworks; soil modification; ground improvement; residential construction

1 INTRODUCTION

Use of modified soils has traditionally been used in the road and pavement industry in the UK. The primary purpose in these industries is to stiffen subgrade soils and minimise expensive sub-base and base courses of pavement construction.

Modification techniques (see Figure 1) have cautiously been used in other construction sectors, including residential construction. The industry at large has been hesitant in adopting modified soils as bulk structural upfills owing mainly to issues with sulphate-induced swelling and difficulties with binder control during the treatment process. However, there has been a growing body of successful residential construction projects, particularly in the north of the UK where soils are not prone to sulphate-induced issues. Here lime, cement and lime/cement combinations have been used to modify substantial bulk upfilling.

The focus of this paper is the compaction characteristics of modified soils in the context of achieving density-driven specifications for structural upfills, typically comprising of requirements for compaction to 95% of maximum dry density and 5% maximum air voids. Onerous specification requirements of this nature have become the norm in residential construction projects.

Figure 1. Lime modification for upfilling of construction podium (courtesy of Ground Developments Ltd)

2 BACKGROUND

2.1 Lime modification

Hilt & Davidson (1960) proposed a correlation for optimum lime content in treated soil as being proportional to the clay content as follows:

$$\frac{\%\,clay}{35} + 1.25 \qquad (1)$$

The associated mechanisms of lime modification are summarised as follows:

Hydration: when quicklime (CaO) comes in contact with the soil porewater, an exothermic reaction occurs producing calcium hydroxide ($Ca(OH)_2$) and heat. The calcium hydroxide disassociates from the water increasing the electrolytic concentration and the pH of the porewater. This results in the dissolution of the soil silica (SiO_2) and soil alumina (Al_2O_3). This process of hydration sets up the follow-on processes.

Ion exchange and flocculation: the prescence of carbonic acid (H_2CO_3) in the native soil – a derivative of the presence of carbon dioxide and the porewater – transforms the calcium hydroxide which disassociates into Ca^{++} and $(OH)^-$, i.e. a cation exchange. This modifies the electrical surface forces of the clay minerals. This occurs with time and, visually, structural change in the soil can now be observed. The soil becomes friable and the particles coagulate and flocculate. At this point the plasticity of the clay is reduced markedly and the material is, thus, more workable. The material is now placed and compacted.

Pozzolanic reaction: secondary pozzolanic by-products are produced with time as the dissolved SiO_2 and Al_2O_3 react with the Ca^{++} ions to form hydrated gels (calcium silicate hydrate and / or calcium aluminate hydrates) which bind the particles. Of note is that the time required for this process is substantially slower than that of a cement hydration process – it is typically days after the initial introduction of the lime to the soil.

Carbonation: a tertiary process wherein the free lime, with time, reacts with atmospheric carbon dioxide to form calcium (or magnesium) carbonates – a weak cementing agent. It has been conjectured (Diamond & Kinter, 1965) that the carbonation process is potentially deleterious rather than beneficial to the finished material.

It should be noted that the pozzolanic and carbonation by-products are considered negligible processes to the preparation of structural upfills. It is the structural change and plasticity reduction from the ion exchange, which faciliates compaction, that is primary.

2.2 Cement modification

In contrast to lime modification, use of cement is purposefully for the production of hydration by-products to engender mass strength improvement. Cement is nominally used where the liquid limit of the material is less than 45% and plasticity index is less than 20, i.e. where the clay content is low and the material is tending towards more granular behaviour. Lime / cement combinations may be used where the natural moisture content is initially high, requiring a reduction (using lime) in order to make it amenable to the cement addition.

Portland cement is comprised of four primary constituents, being tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium alumino-ferrite (C_4A). These compounds react with the soil porewater resulting in massive and rapid hydration. The primary cementitious by-products (hydrated gels) are hydrated calcium silicates (C_2SH_x, $C_3S_2H_x$) and hydrated calcium aluminates (C_3AH_x, C_4AH_x). Calcium hydroxide ($Ca(OH)_2$) is also produced remaining in a crystalline solid phase (note: where the pH is adequately elevated, the same processes of ion exchange and flocculation occur as with lime modification).

2.3 Binder spreading, mixing & compaction

Mixing and compaction is normally undertaken with specialist plant, see Figure 2. Spreaders and mixers are typically proprietary systems designed to facilitate high levels of control on binder addition and mixing quality.

Kennedy & Bregulla (2017) provide useful guidance on the construction processes and quality control of modified soil for use in fills for residential construction projects. The experience gathered in the preparation of this paper has underscored the need for a high level of site-control and adherence to placement & compaction protocols to ensure success in preparation of materials to be compliant with onerous structural upfill specifications.

Figure 2. Specialist plant used in soil modification (courtesy of Ground Developments Ltd)

3 DATA

3.1 Sites

The data used in the preparation of this paper was collected from 8 residential construction projects mainly in Scotland (northern UK), comprising approximately 1,200 residential units, the majority constructed on modified structural upfills.

For commercial reasons, the precise details of each site will not be disclosed. However, the nature of the native ground conditions at the sites typically comprise natural clays and cohesive glacial tills. For all sites, native cohesive materials classified either as Class 2A/B materials or Class 2C materials in line with the UK Specification of Highways Works Volume 1 Series 600.

3.2 Compaction data

Reference densities and measurements of optimum moisture content presented here were derived from 4.5kg rammer 5-point compaction tests in line with BS 1377-4:1990. Measurements of compaction from the field were undertaken with the nuclear density gauge in line with BS 1377-9:1990 corroborated with either the sand replacement test or core cutter test, suitable for the soil type, in line with the same code of practice.

All data was collected in the course of routine quality control testing for the various projects. No selection bias was used in selecting data, except that the sites from which the data was obtained comprised site-won natural and predominantly cohesive materials. Sites with coarse-grained materials as upfill are not represented here as a particular criteria. In total, the collected data comprises 749 individual measurements of relative compaction with associated measurement of bulk & dry density and natural moisture content. The associated reference density (laboratory-derived data) comprised 105 individual tests, measuring maximum dry density and optimum moisture content directly.

4 RESULTS

4.1 Reference density

Figure 3 shows the summary of reference density data plotted against optimum moisture content. Notwithstanding that this data is derived from multiple sources over a wide geographical footprint, the trend correlates well ($R^2 = 0.864$) to a power law. A lower bound envelope is also plotted (lower bound as it relates to assessment of compaction data – see Section 4.3) which encompasses 98.1% of the total data points.

For completeness the non-linear term for the lower bound envelope is as follows:

$$y = 125x^{-3.407}$$

4.2 Descriptive statistics

A set of descriptive statistics is presented for reference in Table 1. This table is provided for background on the field measurements for the compaction data.

It is noted that these statistics taken in isolation offer no tangible inferences but are important as background to the dataset presented here. It is considered that these statistics offer an insight into the nature of the data as would normally be undertaken in the course of an exploratory data analysis for any dataset.

4.3 Summary of compaction data

Figure 4 below presents moisture content plotted against maximum dry density as measured in the field. Collectively, the data form a strong linear trend ($R^2 = 0.85$) noting that the broader dataset is bounded between moisture contents of between 7% and 25% and maximum dry densities between 1.55Mg/m^3 and 2.1Mg/m^3 generally. The 5% air voids curves are plotted for reasonable and practical measures of particle density (2.55 to 2.65). Collectively, all but isolated datapoints express air voids less than 5% and the linear trend plots wholly less than the 5% air voids curve in the parameter ranges. The associated sample covariance is -0.2969.

A histogram, with cumulative density plot, of compaction data is presented in Figure 5. The data is presented for both the trend of reference density and adjusted for the lower bound envelope indicated in Figure 3 above.

The data approaches a normal distribution. Cumulatively, very high relative compaction was consistently achieved. For the lower bound envelope of reference density, less than 2% of the data measured achieved relative compaction less than 95%. For the trend reference density, all relative compaction results are greater than 96%.

Figure 6 presents a summary of measured moisture content plotted against relative compaction. There is no discernible trend to this data. Windows are also plotted based on the mean and standard deviations of both parameters.

While general in its construction, this chart also demostrates the remarkable consistency of the results in terms of compaction achieved over a wide range of moisture contents.

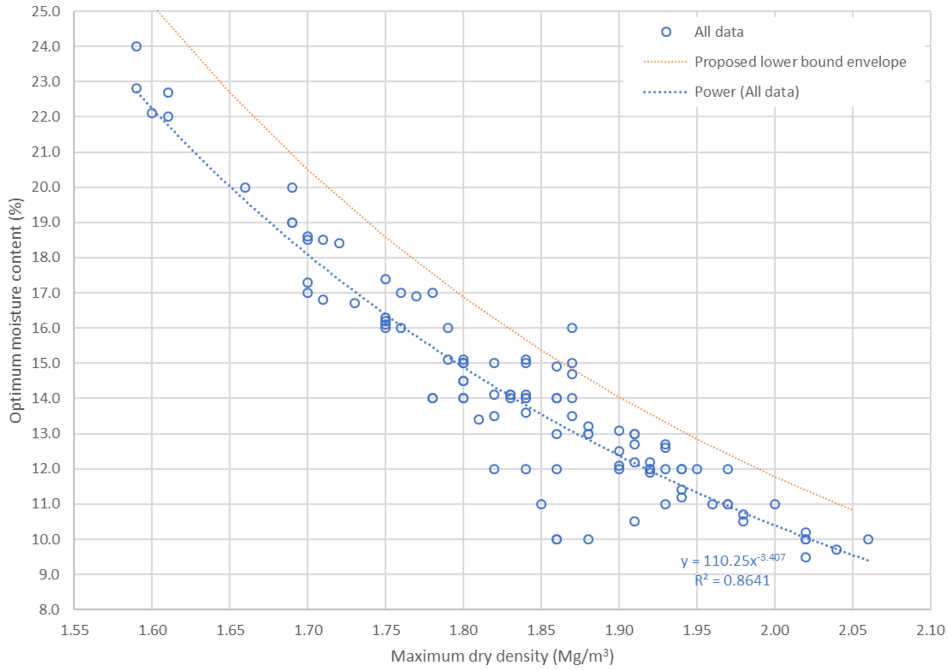

Figure 3. Summary of reference density data with associated trends

Statistical measure	**Moisture content (%)**	**Bulk density (Mg/m^3)**	**Dry Density (Mg/m^3)**	**Compaction (%)**
Mean	14.689	2.126	1.861	98.521
Standard Error	0.113	0.003	0.004	0.087
Median	14.700	2.144	1.880	98.592
Mode	15.000	2.100	1.835	98.472
Standard Deviation	3.098	0.075	0.104	2.373
Sample Variance	9.598	0.006	0.011	5.633
Kurtosis	1.112	-0.354	0.133	0.187
Skewness	0.904	-0.394	-0.543	0.122
Range	17.000	0.364	0.510	18.226
Minimum	8.400	1.940	1.577	91.757
Maximum	25.400	2.304	2.088	109.983
Count	749	749	749	749
Confidence Level (95.0%)	0.2222	0.0054	0.0075	0.1702

Table 1. Descriptive statistics for field compaction data

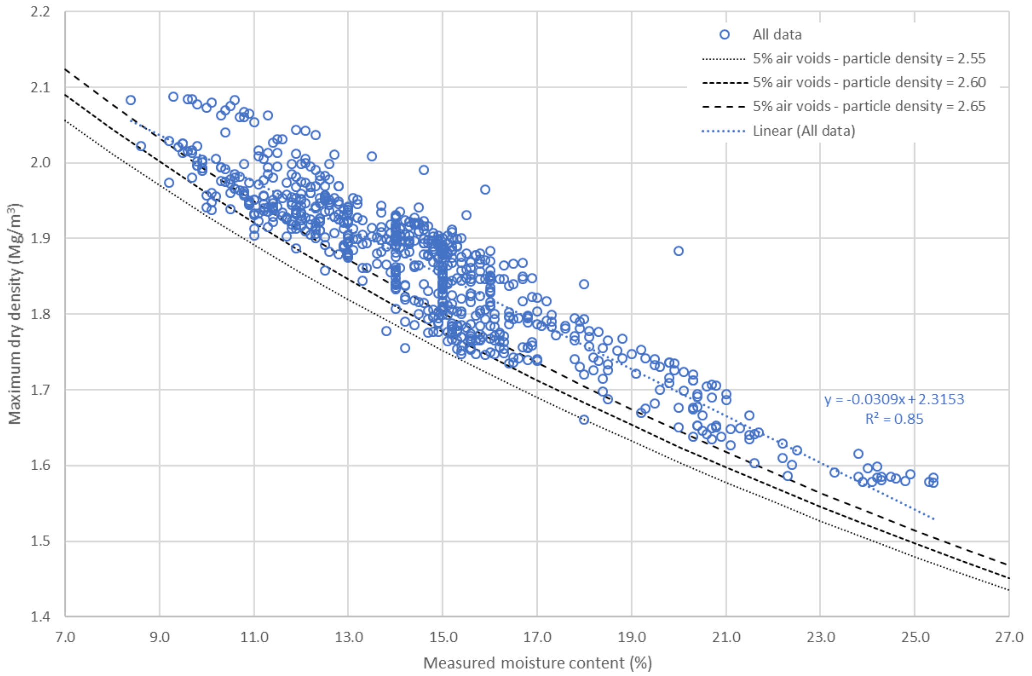

Figure 4. Summary of measured moisture content and maximum dry density from field measurements

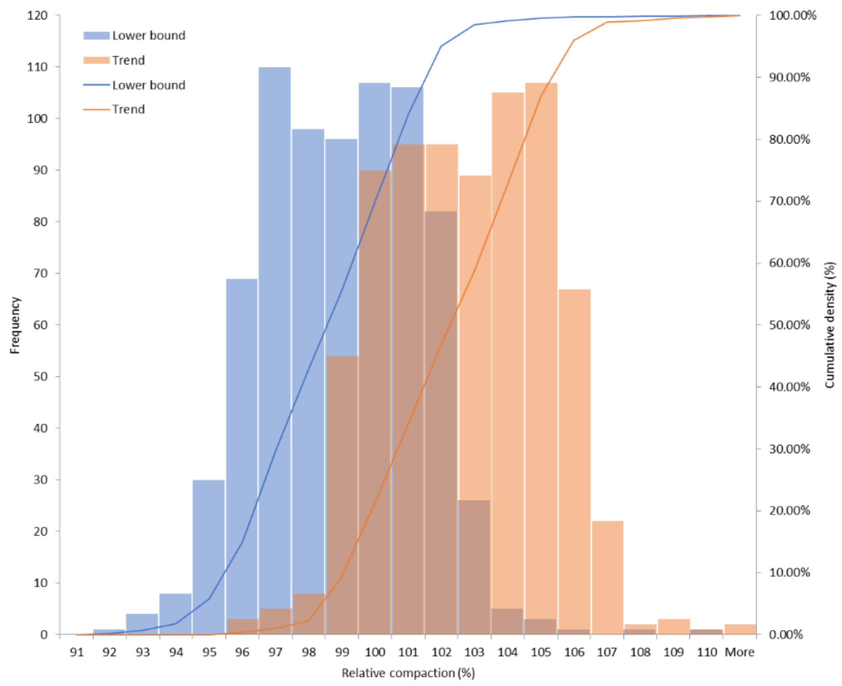

Figure 5. Histogram of field measurements of compaction data for reference density ranges

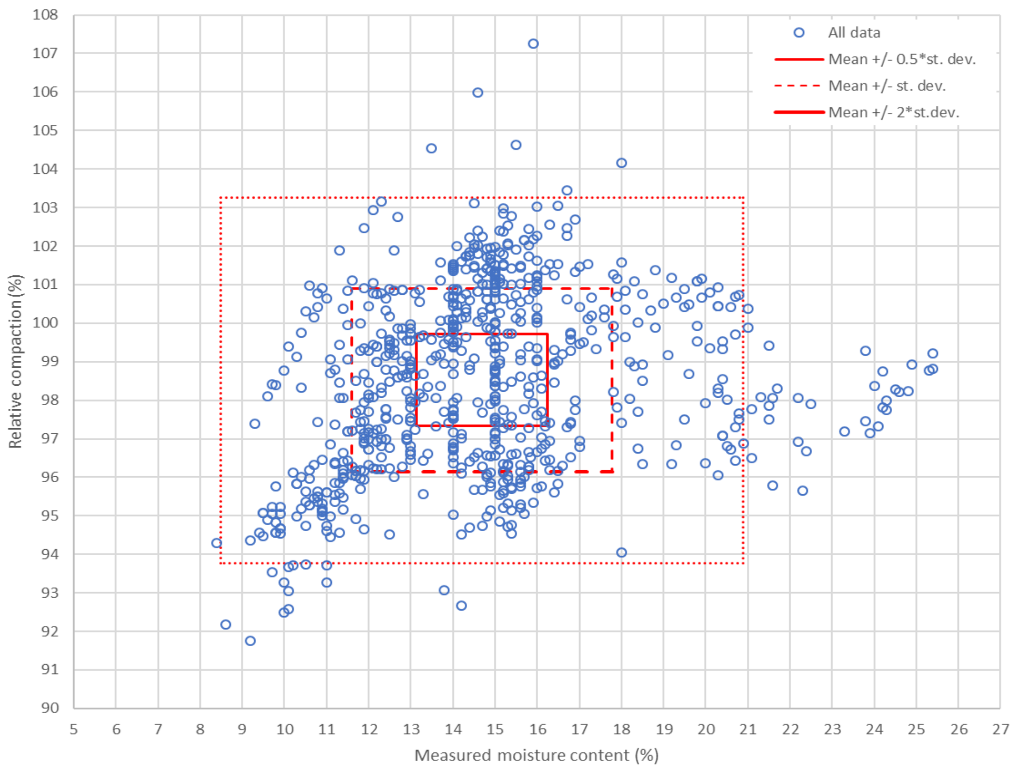

Figure 6. Summary of field measurements of moisture content and relative compaction

5 CONCLUSIONS

A database of field compaction measurements has been presented for modified fine-grained soils from residential construction projects. The data shows remarkable consistency in terms of achieving relative compaction in excess of 95% and air voids less than 5%.

It is considered that modification of soils, in conjunction with good site procedures and construction practices, substantiated with rigorous quality control, provides a reliable product in the achievement of onerous density-driven specifications for structural upfill in residential construction projects.

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