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PERFORMANCE PARAMETERS OF REALISTICALLY CURED LIME-TREATED OXFORD CLAY CAPPING LAYERS FOR ANALYTICAL PAVEMENT DESIGN

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ABSTRACT

A significant amount of research has been carried out in the UK during the last decade in order to establish an analytical specification for pavement foundation design. The new approach aims to establish the performance parameters of the materials prior to designing using modern laboratory testing techniques and hence set target values for the end product. The method seeks to abandon CBR testing, an empirical assessment of disputable effectiveness in establishing detailed design parameters. Research on the performance parameters of untreated soils has been done, however the area of stabilised materials requires further investigation. Clay soils consisting predominantly of illite, such as Oxford Clay, are commonly found in the UK and elsewhere. Due to their mineralogy, these soils are susceptible to water ingress so when they are to be used as pavement subgrades in wet environments it is common to treat them with arbitrary amounts of lime/cement prior to compaction in order to achieve high post-compaction CBR values. The result is uneconomical design as well as a waste of materials, let alone questionable performance. This paper presents the performance parameters of lime-treated Oxford Clay as established through a repeated load triaxial testing regime. Clearly, for the soil used herein, the addition of lime alone at the appropriate amount creates a layer that can confidently be used for pavement foundation construction since it performs satisfactorily under adverse, though realistic, curing and testing conditions.

KEY WORDS: lime stabilisation, resilient modulus, permanent deformation.

1. INTRODUCTION

During the last decade, the need has been emphasized both by the academia and the road construction industry in the UK to develop an analytical method for pavement foundation design. Analytical or performance-based specifications use realistic testing to obtain material's performance parameters in the laboratory prior to construction and hence allow the engineer to become fully aware of the potential of the employed materials to perform under realistic worst case scenario conditions at an early stage of the design process. These parameters are then used, along with other traffic data, to obtain layer thicknesses. The benefits of such an approach are not only of financial nature, since problematic material behaviour can be spotted in time and appropriate measures may be applied, but also of environmental importance since waste of natural aggregates can be avoided.

When dealing with road foundation materials, due to the dynamic nature of loading, the term "*performance parameters*" has to include factors that describe not only the bearing capacity but more importantly the repeated load-deformation characteristics of the materials. Hence, in addition to shear strength, in order to obtain a full description of the mechanical behaviour of the employed materials the Resilient Modulus (M_R) and the development of permanent deformation (δ_P) under increasing levels of repeated stress should be established via repeated load triaxial (RLT) testing [1]. The behaviour of natural clay soils under repeated loading has been investigated [2] however, the lack of research on stabilised clays has caused delays in developing an analytical UK specification that will ideally specify not only the analytical methodology for laboratory testing, but also the minimum performance requirements for the completed pavement foundation as well as the *in-situ* methods and tools of assessing the end-product performance.

2. DESIGN APPROACHES OVERVIEW

When road foundation design is considered, there are either empirical or analytical approaches available. The former use empirical laboratory or *in-situ* testing techniques to characterize the foundation materials and hence decide on layer thickness. Amongst them, the CBR test-based approaches are the most widespread and such a version is currently used in the UK. Accordingly, the foundation material is evaluated via CBR testing and following a sequence of standardized graphs the thickness of the pavement foundation layers is established. However, the need to identify in detail the potential of the employed materials to perform under dynamic loading as well as the necessity to include novel materials such as recycled and stabilised requires more sophisticated laboratory means. The CBR test only provides an empirical index of performance rather than any fundamental geotechnical parameter and therefore cannot be considered a reliable platform for plausible analytical performance conclusions as there is no safe correlation between CBR values and analytical design performance parameters [3].

On the contrary, analytical approaches incorporate into the calculation of the foundation layer thickness laboratory testing data that directly links to the repeated-load deformation characteristics of the foundation materials. An example of such a method is the Flexible Pavement Design Manual [4], where the laboratory calculated M_R is used, alongside other traffic data, to obtain layer thickness for the construction of new as well as the reconstruction of existing pavement foundations. However, establishing an analytical methodology for pavement foundation design is a complicated two-stage process. Initially, the performance parameters of the materials have to be obtained through realistic laboratory testing that accurately replicates worst case scenario field conditions and next, these parameters have to be linked to layer thickness, a process that also requires extensive large scale field trials.

3. AIMS AND OBJECTIVES

This paper aims to build towards filling the gap regarding the lack of laboratory research on the performance parameters of stabilised clays and hence provide a deeper insight on the behaviour of these materials under adverse, though realistic, curing and testing conditions. However, a dual objective is achieved since not only valuable design parameters and behavior trends are obtained but also confidence is gained in using such materials as capping for road foundations.

4. MATERIALS AND METHODOLOGY

4.1 Materials

Illite dominated clay is a commonly found soil. Such clays, tend to absorb greater amounts of water, when available, compared to other clay minerals (e.g. kaolinite) resulting in a soft soil bed unable to support the construction traffic induced stresses and deformations. In order to overcome the problem, a two stage approach is frequently followed. Initially, lime is used in small, but usually arbitrary, amounts as a dewatering agent in order to dry the excessive moisture off the topsoil and then cement is added prior to compaction to provide strength/stiffness. The random nature of this process leads to uneconomical design as well as a waste of materials, let alone questionable performance. It was considered practical to employ such a soil to meet the objectives of this research since, apart from selecting and evaluating analytical design data, a real time problem would be assessed.

Hence, Oxford Clay (OC) consisting of illite (35%), quartz (23%), kaolinite (15%), calcite (14%), pyrite (9%), gypsum (1%), chlorite (1%), feldspar (1%) and plagioclase (1%) was used. The Plasticity Index was found to be 23% and the Initial Consumption of Lime test (ICL) indicated that full modification and stabilisation are achievable with the addition of 3-4% lime (per dry unit weight of the soil).

4.2 Testing Protocol

Extended research on the performance parameters of natural clays under repeated loading showed that M_R decreases rapidly with increasing repeated stress (deviator stress) with the changes being more apparent for stresses less than 50% of the maximum monotonic stress that the soil can carry (q_{max},). Past that level, M_R appeared to experience minor, if none at all, changes suggesting asymptotic tendencies [2]. Around that same stress level δ_p becomes unstable (increases at extremely high rates) leading eventually to rutting and shear failure [2]. Therefore, suggestions have been made to limit the deviator stress to a threshold value (q_{thr}), i.e. 50%q_{max}, in order to prevent subgrade rutting. Limited research on stabilised clays suggests that similar trends are also valid in the cases of lime/cement treated clays [1].

In that context, a program of RLT testing was formulated in order to observe the ability of lime-treated OC to perform under dynamic loading and hence observe changes and trends regarding M_R and δ_P (herein the terms M_R and stiffness are used to describe the ratio of deviator stress to the recoverable strain). Undrained RLT tests were conducted on cylindrical samples (50mm diameter, 100mm length), that had been cured for periods of 3,14 and 72days. Four tests were conducted on each sample and a deviator of 20, 40, 60, and 80% q_{max} was applied for 100 cycles in each test. Q_{max} was measured earlier on sets of three identical samples. The selected stress levels and loading rate (1 load cycle/12 min) were chosen to represent construction traffic conditions (construction vehicles traveling at creep speed and imparting high stresses, relative to the shear strength of the material). The confining stress was kept at 20kPa throughout all triaxial testing, a value that is widely accepted as realistic for establishing analytical design performance parameters via triaxial testing for road subgrade materials [5].

OC was thoroughly mixed with de-ionized water and left sealed for 24h at approximately room temperature. Additional water was then mixed with the soil just before quicklime was added to achieve a lime percentage by weight of 1.0% higher than the ICL value, i.e. 5%. This deviation from the ICL value was adopted to make sure there is enough lime to satisfy all the short-term reactions and yet provide enough lime to sustain the long-term strength producing lime-soil reactions [6]. The mix was sealed for further 24hrs at room temperature in order to allow the lime to migrate through the pulverized clods of the material and hence cause further plasticity changes (mellowing). Cylindrical samples were then manufactured to achieve a water content of 2% wet of the optimum water content and a dry density corresponding to that achieved by the British Standard Heavy Compaction, the equivalent of modified proctor. It is common to stabilise soils a few percent wet of optimum in order to minimize air-voids in the soil structure, whereas the modified proctor was preferred instead of the standard since the levels of compaction that modern machinery can achieve in practice are substantially greater than those of the standard proctor [8]. The water content and dry density, at 2% wet of optimum, were 19.06% and 1.64 Mg/m3 for the untreated clay, and 19.44% and 1.60 Mg/m3 for the lime-treated clay.

4.3 Sample Curing

A curing regime based on capillary saturation under constant confining stress, was employed in order to achieve a reasonable degree of realistic curing [1]. Samples sitting on a saturated porous stone and enclosed in a rubber membrane were placed in a curing chamber and subjected to all-round confinement using pressurized air at 20kPa. Water (non-pressurized) could enter from the base of the sample due to capillary action through the porous stone. The practical conditions following compaction above a relatively soft, wet clay subgrade were thus simulated (i.e., a sealed upper surface, a significant mean normal effective stress due to "locked in" stresses following compaction). Reference to this method is made herein using the term "wet" curing or "wetting". To facilitate comparisons with traditional practice, "dry"-cured specimens (sealed by double wrapping in polyethylene bags) were also tested. In all cases, the temperature was kept constant at 8°C throughout the curing period, an appropriate "worst case" temperature to be expected in the field during the stabilization months in Britain (March to September, shade temperature > 7°C).

5. RESULTS AND DISCUSSION

5.1 Shear Capacity

The monotonic triaxial testing (Figure 1) demonstrated that natural OC, when kept "dry", showed considerable strength (1614kPa). When water was available to the samples for 3 and 14 days (OC WC3 and OC WC14) q_{max} dropped to 955 and 280kPa respectively confirming that water absorption directly affects shear strength. The total strain differences, under the same deviator stress, recorded for each of the three states were dramatic with the "wet" samples experiencing much higher deformations.

The addition of lime resulted in substantial strength increase for the "dry"-cured samples even in the early 14days (OCL DC14) that continued at least up to 72days. Indeed, in the case of lime-treated OC, early strength gain was expected since cementitious products that bond the clay particles together form before the first two weeks [8]. Hence, q_{max} climbed from 1445kPa (OCL DC3) and 1688kPa (OCL DC14) to 2270kPa after 72days (OCL DC72) demonstrating the cementation progress. Total strains decreased with curing time indicating significant stiffness improvement.

The addition of lime prevented the dramatic loss of strength due to water absorption in the cases where water was available to the soil, even for as long periods as 72days, and also reduced total strains. Overall, the q_{max} of the "wet" lime-treated OC was reduced compared to the "dry" natural OC however, even after 72days of "wetting" (OCL WC72), the lime-treated samples reached a q_{max} of 1257kPa signifying that lime acted beneficially maintaining a large portion of the natural soil's strength and resistance to deformation compared to the untreated "wet" OC specimens which showed complete degradation upon wetting. Interestingly, the q_{max} after 14days of "wetting" dropped from 1230kPa (OCL WC3) to 833 (OCL WC14) indicating that the presence of water limited/delayed early cementation. Nevertheless, the fact that strength increased and total strains reduced after 72days suggested that the cementitious activity occurred after 14days.

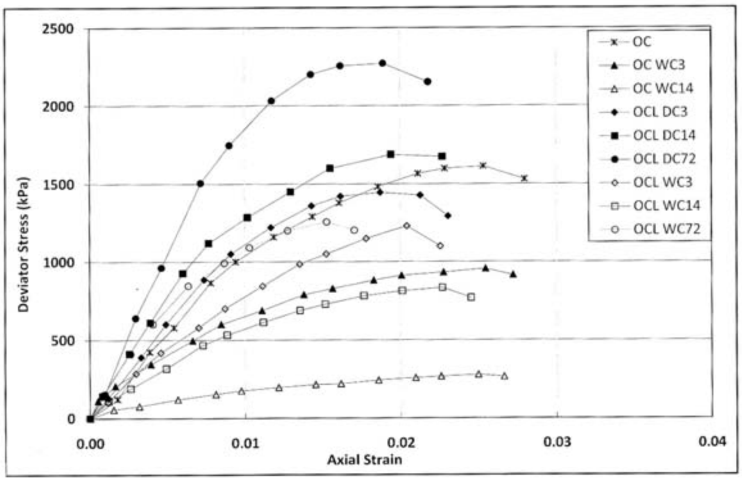

Figure 1: Undrained Shear Capacity for the Lime-Treated and Untreated Oxford Clay.

5.2 Resilient Modulus (M_R) and Permanent Deformation (δ_P)

The M_R curves (Figure 2) for the natural OC agreed with the q_{max} trends suggesting an inverse water content-M_R relationship, i.e. the longer the "wetting" the lower the moduli. The modulus of the "dry" OC experienced large decline (from 240 to 122MPa) with increasing deviator stress up to the 80% q_{max} test where shear failure occurred before any asymptotic tendencies were apparent. A close examination of the δ_P curves (Figure 3) showed stable permanent deformation for the 20 and 40% q_{max} test (permanent strains reach or tend towards a constant value with increasing number of cycles under constant repeated stress) and unstable during the 60% and 80% tests (permanent strains increase rapidly with the number of cycles towards shear failure) indicating that q_{thr} fell within the range of 40-60% q_{max}, a stress range consistent with the 50% q_{max} that literature suggests. The M_R of the untreated "wet" soil followed the asymptotic tendencies suggested by literature and in both cases (3 and 14days) stiffness changes became less noticeable after the application of 40-60% q_{max}. The moduli dropped from 224 to 70MPa and 76 to 35MPa for the "wet" natural soil after 3 and 14days respectively indicating that "wetting" affected harmfully the resilient properties. The observation of δ_P revealed in both cases that permanent strain remained stable during the 20 and 40% q_{max} test and unstable after that indicating that q_{thr} rested within the 40-60% q_{max} range.

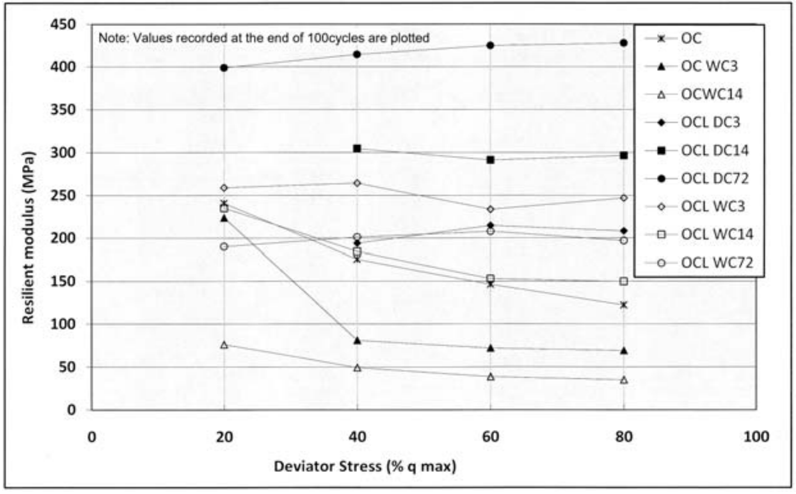

Figure 2: Variation of the Resilient Modulus with Increasing Deviator Stress for the Lime-treated and Untreated Oxford Clay.

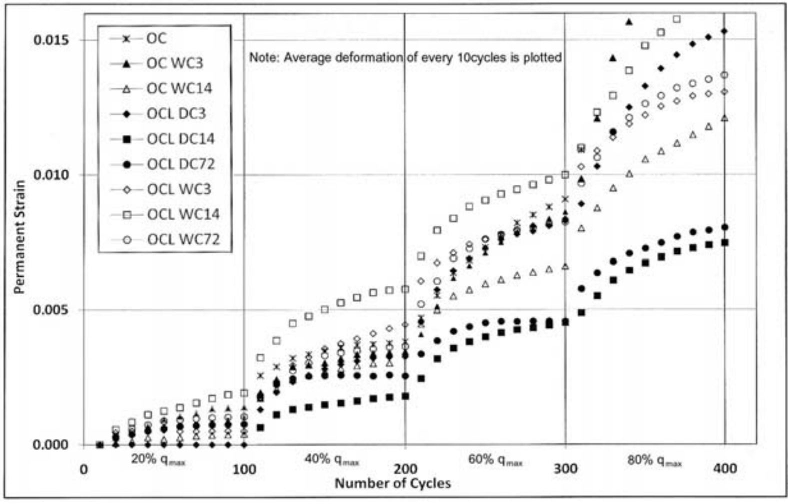

Figure 3: Development of Permanent Deformation with Increasing Number of Cycles and Deviator Stress for the Lime-Treated and Untreated Oxford Clay.

Regarding the “dry” lime-treated OC, the stiffness improvement indications suggested by q_{max} were partly confirmed. The samples cured for 14 and 72days developed significantly higher moduli compared to that of the 3days and the untreated OC, however the M_R changes that occurred with curing time proved that the stiffness growth was significantly larger than that suggested by the q_{max} graphs. Overall, the M_R values varied between 195 and 430MPa confirming that the addition of lime significantly improved the elastic properties of the material under repeated loading. The increased M_R values in the first 14 days (around 300MPa) reinforces further the argument that for this type of clay the formation of cementitious products is underway before the first 14days. Regarding the tendencies of the graphs, M_R dropped with increasing deviator stress in the cases of 3 and 14days of curing and reached a constant of around 200 and 300MPa respectively after the application of 40% q_{max} (the deviator of 20% q_{max}, in both cases caused minor elastic strains resulting in extremely high moduli and for that reason these values have not been plotted). On the other hand, after 72days of "dry" curing, M_R appeared to be reaching a constant immediately a fact that could be attributed to the extended cementation. Regarding the development of δ_P, in the case of OCL DC3 (i.e. soil modified but not yet stabilised) the q_{thr} appeared to fall within the 40-60% q_{max} range, as in the untreated OC, since unstable δ_P occurred during and after the 60% q_{max} application. In the case of 14 and 72 days it appears that the location of q_{thr} was clearly affected by the advanced cementation that reinforced the soil structure since δ_P appeared to be stable throughout all stress levels.

When water was available to the lime-treated soil, the trends observed via the q_{max} testing were not confirmed by the M_R changes. In all cases, the modulus of the lime-treated soil experienced significantly higher values compared to both the "dry" and "wet" untreated soil despite the fact that the q_{max} graphs suggested otherwise. Overall, the M_R values for the "wet" cured lime-treated soil varied between 150 and 250MPa as opposed to a variation between 35 and 150MPa of the untreated indicating major performance improvement despite the fact that water delayed/compromised, to an extent, the long-term stabilisation reactions, a hypothesis that is also confirmed by the higher M_R values of the "dry" cured lime-treated material. Regarding the general trends, M_R did not experience further changes during the 60 and 80% q_{max} tests in the cases of 3 and 14days of "wetting" whereas it remained constant throughout for the 72days cured sample, as in the case of 72days of "dry" curing, a fact that further reinforces the argument that this stiffness stability (i.e. elastic deformation directly proportional to the applied stress) regardless the stress level (at least in the range 20-80% q_{max}) can be attributed to the extended degree of cementation that took place after 14days of curing. In terms of q_{thr}, the permanent deformation of the OCL WC3 sample fell into the unstable state relatively early, i.e. in the range 20-40% since almost linear increases of δ_P were observed at and after the 40% q_{max} test indicating that in the early days the water availability and absorption did not improve the resistance to permanent deformation. However, the OCL WC14 and OCL WC72 samples showed that, as cementation progressed, the samples became more resistant to permanent strain moving the location of q_{thr} in the usual range of 40-60% q_{max}.

The improvement as far as resistance to permanent deformation is concerned is more apparent when the absolute values of q_{thr} are plotted for each mix and curing period (Figure 4). Clearly, the natural soil became more susceptible to permanent deformation upon wetting, while when stabilised with lime and kept "dry" the improvement was dramatic and proportional to the curing time. Significant improvement was also observed with curing in the case of the "wet" lime-treated soil. Hence, the value of q_{thr} kept increasing with curing time and after 72days of "wetting" it reached 503kPa, a value that is significantly higher than those of the "wet" untreated soil clearly demonstrating progressive improvement. In practical terms, it has been reported that (for a given load) single-axle vehicles acquire greater stresses on the foundation than multi-axle vehicles [9]. Hence, considering a single-axle (say 2-wheels on each side) load of 8,2tons (recommended value as an upper boundary for single-axle loads [9]), the resulted stress is around 293kPa. This means that the stabilised material can easily cope with these stresses immediately after mixing and compaction when kept "dry" and even if "wet" it will carry the load, and more, in less than two weeks after compaction without any danger of rutting due to excessive permanent deformation provided that q_{thr} is not exceeded.

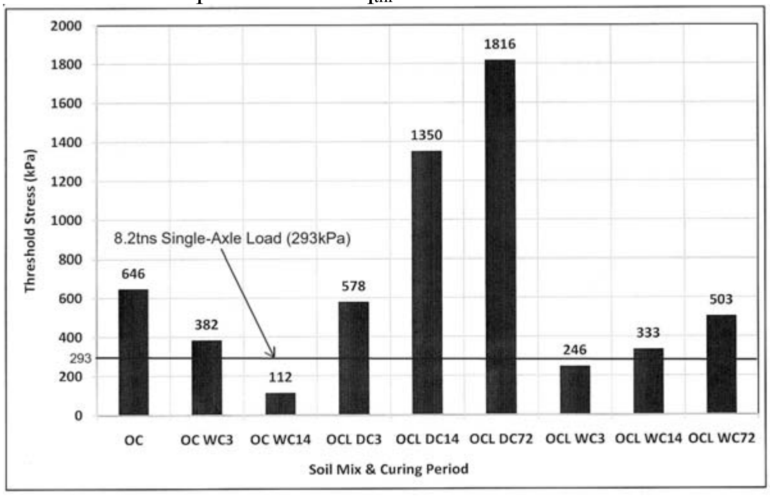

Figure 4: Threshold Stress Development for the Lime-Treated and Untreated Oxford Clay.

6. CONCLUSIONS

In order to evaluate the performance parameters of lime stabilised clays both monotonic and RLT testing are necessary. However, this research recommends the results of each be examined independently since any assumptions based on q_{max} graphs regarding M_R and δ_P are at high risk and not accurate. The authors suggest that only q_{max} should be obtained from monotonic testing and then used as a basis for the applied repeated load stresses regime in order to obtain M_R and q_{thr}. In turn, although the development and variations of M_R and δ_P are acquired from the same RLT testing, the results should also be examined autonomously and with care the reason being that elastic and plastic deformations progress differently. Hence, in the majority of cases, it was observed that while the M_R was at relatively high ranges, δ_P was simultaneously at an unstable state moving towards rutting and shear failure. Therefore, the authors believe that it is equally important, if not more, for performance-based specifications to incorporate, alongside design M_R, limiting q_{thr} values as well.

The addition of lime to OC, at the recommended amounts, ensures significantly increased q_{max}, M_R and q_{thr} provided that the layer is safely guarded against water ingress. In the cases of very wet environments, the addition of lime will preserve a large portion of the pre-"wetting" strength of the material while it will improve M_R and keep q_{thr} at high levels, compared to the untreated OC. In that case, the authors recommend loading of the layer two weeks after mixing and compaction when improvement has clearly progressed.

The location of q_{thr}, regarding the treated material appeared to be affected by intense cementation, and prolonged "wetting", however, the level of 50% q_{max} that applies for the untreated clays seems to be a reasonable value to estimate q_{thr} for lime-treated OC if RLT testing cannot be used.

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