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Some observations on the design and construction of wet soil mixing in the UK

Quelques observations sur la conception et la construction de mélanges de sol humide au Royaume-Uni

A. O’Brien
GE Solutions Consulting Ltd, Whitburn, Scotland

ABSTRACT: Mass soil mixing and deep soil mix columns are a versatile ground improvement technology for marginal and brownfield sites. Dry soil mixing is relatively common in the UK for improvement of ground with very wet and/or organic material. Wet mixing is less commonplace and involves introduction of a fluid grout with simultaneous disaggregation of the soil with a rotating mixing tool. This paper presents the results of strength verification testing carried out across multiple projects in the UK covering differing soil types with varying project specification criteria. Some conclusions are drawn with regards to the factors affecting strength progression and in understanding the mechanics of the mixing process. Mixing time per unit volume of mixed material is identified as an important parameter for mass mixing. In addition, discrete element modelling has shown promise in understanding the mechanics of deep column mixing.

RÉSUMÉ: Les colonnes de mélange de sol en masse et de mélange de sol en profondeur constituent une technologie polyvalente d'amélioration du sol pour les terrains marginaux et les sites contaminés. Au Royaume-Uni, le mélange de sol sec est relativement courant pour améliorer le sol avec des matières très humides et / ou organiques. Le mélange humide est moins courant et implique l'introduction d'un coulis fluide avec une désagrégation simultanée du sol avec un outil de mélange rotatif. Ce document présente les résultats d’essais de vérification de la résistance menés au Royaume-Uni dans plusieurs projets couvrant différents types de sol et différents critères de spécification de projet. Certaines conclusions sont tirées en ce qui concerne les facteurs influant sur la progression de la résistance et sur la compréhension des mécanismes du processus de mélange. Le temps de mélange par unité de volume de matériau mélangé est identifié comme un paramètre important pour le mélange en masse. En outre, la modélisation discrète éléments s’est révélée prometteuse pour comprendre les mécanismes du mélange en colonne profonde.

Keywords: deep soil mixing; mass mixing; soft ground; ground improvement; discrete element modelling

1 INTRODUCTION

Ground improvement technologies are used extensively in the civil engineering and building industries to engender higher strength, lower compressibility or improvement of other engineering properties into native soils for the purposes of accommodating greater load or achieving a greater level of serviceability for a structure than would have otherwise been possible. Success of these methods are prevalent in Japan, the United States of America, Scandinavia, Great Britain and Ireland (Munfakh, 1997; Terashi & Tanaka, 1981; Hebib & Farrell, 2004) having been pioneered initially and independently in Japan and Scandinavia.

In extensive and deep deposits of soft ground, deep soil mixing, traditionally encompassing the mechanical agitation of ground with the addition of a cementitious or lime binder, is commonplace as an improvement method. The chemical processes of binder introduction, (i.e. hydration & subsequent production of primary & secondary cementitious by-products, ion exchange & flocculation, pozzolanic reaction and carbonation), are well understood with well-defined relationships between the volume of binder introduced and the strength and/or stiffness increase (for a given binder type or blend). However, the mechanics of the mixing processes are not well understood.

1.1 Soil mixed columns

Soil mixed columns find particular application in the treatment of deep deposits of poor materials. Typically the columns are combined with a soil mixed load transfer platform to provide a working formation of high bearing capacity. Other applications include settlement reducing techniques and cut-off walls.

Figure 1 shows a proprietary rig-mounted wet soil mixing system known colloqially as Turbojet (developed by Trevi Soilmec) which will be a focus of this paper. The system involves penetration of a mixing tool at high revolutions per minute in conjunction with the introduction of liquid grout under high pressure (typically in excess of 250 bar). A typical mixing tool is shown in Figure 2. The combination of the high number of blade rotations per unit depth and the disaggregation engendered by the grout under high pressure results in complete destructuring of the native soil and, thus, high quality mixed soil.

The system is considered to be a hydrid of mechanical soil mixing and jet grouting technologies – its primary advantages being the facility to work effectively in a broader range of soil parameters, both granular & cohesive, including high plasticity clays and high production rates. Wet soil mixing techniques are sub-optimal for soils of natural moisture content in excess of 100% where the native water content diminishes the effect of grout addition. The governing construction parameter is the blade rotation number (BRN), defined in EN 14679:2005.

Figure 1. Turbojet system for deep soil mixing (courtesy of Ground Developments Ltd)

Figure 2. Turbojet mixing tool (courtesy of Ground Developments Ltd)

1.2 Mass mixing

Mass mixing (see Figure 3) involves disaggregation of the soil using an excavator-mounted rotavating tool (see Figure 4). In general, the principle is the same as deep columns however mixing usually takes place within discrete "cells" and depth is limited up to 5-7m depending on the application and native soil.

The rotavating tool spins at high revolutions per minute (in the order of 80-90rpm) and grout is injected under medium pressure. The result is a completely fluidised cell and mixing time per cell is conjectured to be critical to homogenising the material and engendering the required strength.

Figure 3. Mass mixing system (courtesy of Ground Developments Ltd)

Figure 4. Mass mixing tool (courtesy of Ground Developments Ltd)

2 BACKGROUND TO PROJECTS

The projects which are the subject of this paper cover northern England and Scotland as shown in Figure 5. Table 1 compares and contrasts the projects in terms of ground conditions and soil mixing types. In all cases, groundwater was near (within 1m) commencement level.

Figure 5. UK project locations

Project location	Indicative soil type	Mixing type / depth
Walney	Tidal flats, very soft, sensitive CLAY	Deep columns up to 25m deep
Dundee	Infilled quarry, uncontrolled granular fill & waste (ash)	Deep columns up to 17m deep
Airdrie	Granular Made Ground with PEAT lenses up to 1.5m thick	Mass mixing up to 4m deep
Stonehouse	Very soft, sensitive CLAY	Mass mixing up to 5m deep
Aberdeen	Very soft SILT with marine influence	Mass mixing up to 6m deep

Table 1. Summary of project conditions

3 OBSERVATIONS

3.1 Deep soil mixing

While the focus of this paper is on the laboratory strength testing for routine quality control of soil mixing, it is important to note that laboratory tests should be augmented by visual-manual inspection where appropriate. This can be undertaken by exposing mixed material (see Figure 6 which shows the head of a soil mixed column exposed) and through extraction of rotary cores post-construction (see Figure 7).

Figure 6. Exposed soil mixed column (courtesy of Ground Developments Ltd)

Figure 7. Partial rotary core through soil mix column (courtesy of Ground Developments Ltd)

3.1.1 Density

In routine strength testing, undertaken as unconfined compressive strength testing of manufactured cubes of samples extracted from site, density of the sample is normally measured. Observations have not demonstrated any reliable correlation of strength and sample density. In Figures 6 & 7 below, strength and density are compared for 14-day and 28-day cured samples from the Walney and Dundee sites.

The Dundee data has inherently lower density owing to the nature of the native mixed soil, being of granular, ash & waste composition and this is reflected in the mixed material. However, this has not affected the overall strength gain. Both sets of results express similar strengths (both sites had equal target design strengths).

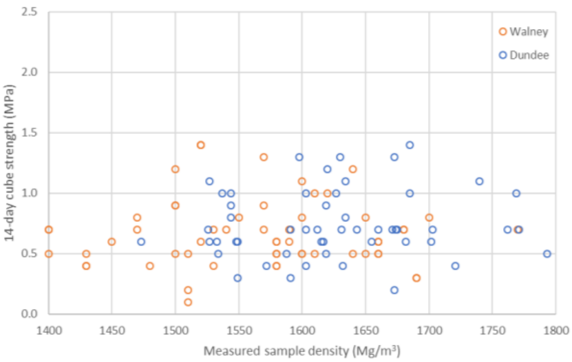

Figure 8. 14-day strength-density plots

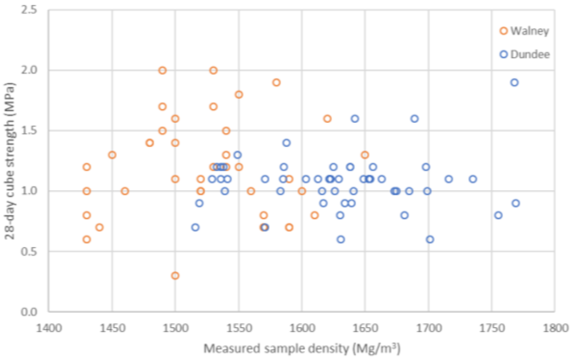

Figure 9. 28-day strength-density plots

3.1.2 Laboratory strength

Histograms are presented in Figures 8 & 9 for the strength measurement from the Dundee & Walney sites for 14-day and 28-day strengths respectively. The results indicate a normal distribution but with a hint of right skew on the 7-day results. Standard deviations for the 14-day & 28-day results were 0.34MN/m^2 & 0.25MN/m^2 respectively – the target 28-day strength was 1.0MN/m^2.

The Dundee (predominantly granular) data cumulatively expressed more rapid strength gain. However, at 28 days the Walney (predominantly cohesive) data had exceeded the Dundee strength cumulatively.

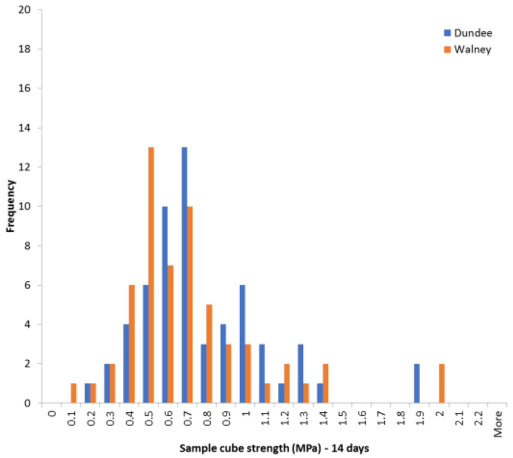

Figure 10. Histogram of 14-day strength test results

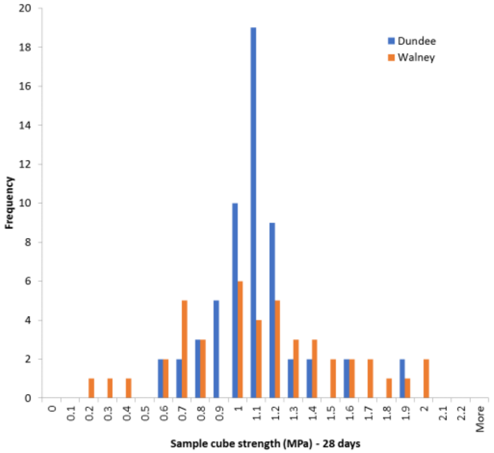

Figure 11. Histogram of 28-day strength test results

The mean 14-, 28- & 48-day strengths are presented in Figure 12 below. The data was found to fit well with the relationship of Åhnberg (2006) as follows:

$$\frac{q_t}{q_{28}} \approx 0.3 \cdot \ln t$$

Where: q_t is the strength at time t
q_{28} is the strength at 28-days

However it should be noted that the sample size for 48-days is comparably small. For statistical completeness, the associated box plots for the Dundee & Walney strength data are presented in Figures 13 & 14 below respectively.

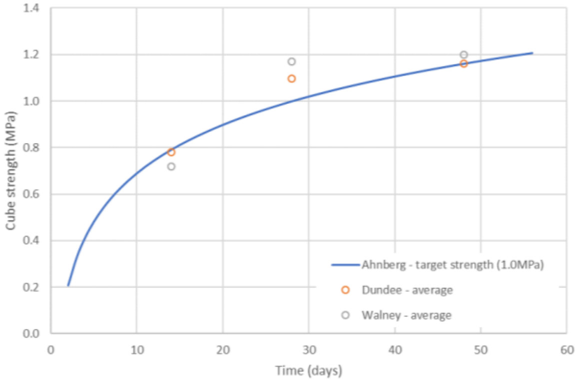

Figure 12. Strength gain of mixed material from column samples

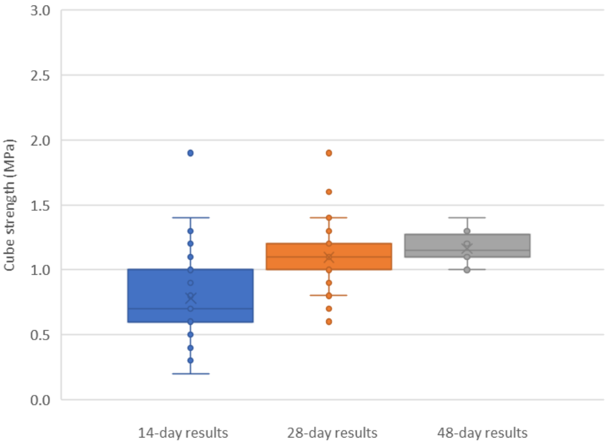

Figure 13. Box plot of strength results for Dundee

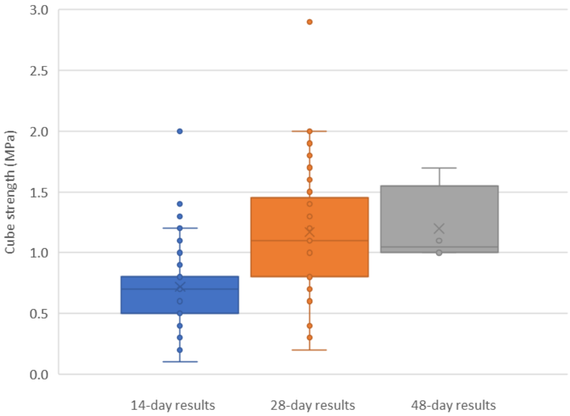

Figure 14. *Box plot of strength for Walney*

3.2 Mass mixing

The mass mixing system is a versatile tool with applications in both permanent & temporary works. The range of projects considered here (Airdrie, Stonehouse & Aberdeen) included bearing capacity improvement for a retaining wall, car-park and large silo tanks. Other applications include stabilisation of deep extremely soft soil for workability, cut-off walls for groundwater & ground gas and improvement of passive soils in cofferdams for temporary excavation support.

The design of the rotavating head itself is specific to soil type. Figure 15 below shows a head more suited to cohesive soils where as the head shown in Figure 4 is more suited to granular materials.

Figure 15. Alternative mixing head (courtesy of Ground Developments Ltd)

3.2.1 *Mixing time*

Experience has shown that mixing time is critical to the success of mass mixing procedures. Specifically, mixing time per unit volume of material in each cell is conjectured to be a critical measure to ensure adequate strength gain and homogenity of the mixed material.

In the mass mixing projects discussed here, the veracity of this perception is examined from full-scale project data. Mixing time is plotted against strength gain in Figures 16 & 17 below for 7/14-day and 28-day strength measurements. However, given that the mix design is markedly different for the Aberdeen project, these results have been normalised by q* (considered as the mean result plus one-half of a standard deviation from the mean as an upper bound of the results) and presented in Figure 18.

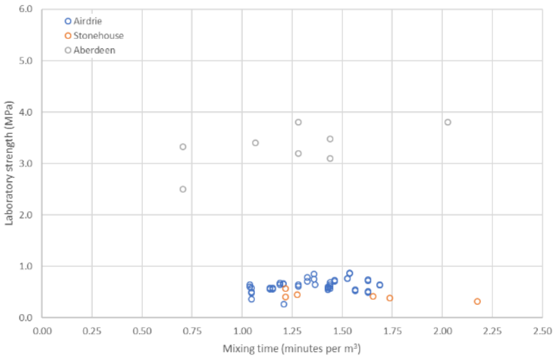

Figure 16. 7-day to 14-day strength & mixing time results for mass mixed sites

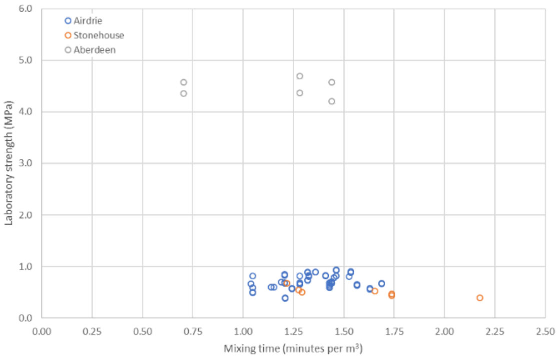

Figure 17. 28-day strength & mixing time results for mass mixed sites

The normalised plot shows that mixing time potentially has an optimal minimum of between 1.5 and 1.75 minutes. In statistical terms, the sample range is too narrow to propose a reasonable model but there is evidence of a peak (and thus optimal) mixing time where strength gain is maximised.

The data strongly indicates that mixing time less than 1.0 minutes has a detrimental effect on strength gain. Equally, there is evidence of a tapering off of strength gain with mixing time in excess of 1.5 to 1.75 minutes.

These observations are very important in terms of developing project specifications where wet mass mixing is proposed. Mixing time per unit volume should be considered as a primary control parameter. Soil mixing does not currently have a standardised specification in the UK. Typically, projects where soil mixing is proposed will have a bespoke specification identifying geotechnical properties for the mixed material. EN 14679:2005 is normally proposed as a guiding code of practice. While the BRN is a useful control parameter for deep columns, there is no equivalent control parameter for mass mixing appartus. Mixing time per unit volume appears to be a purposeful measure to this end.

Further work and data collection over a wider range of mixing times is needed to form a firmer view on the precise relationship between mixing time and strength gain.

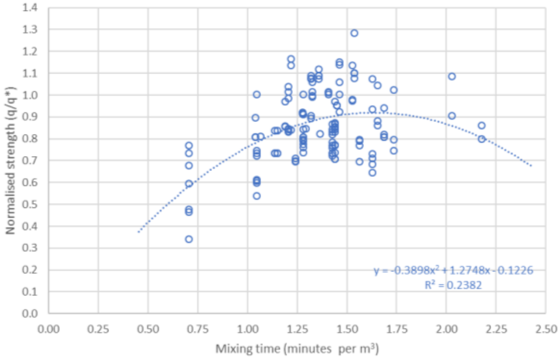

Figure 18. Relationship of mixing time and strength development

4 FUTURE WORK & RESEARCH

4.1 Data development

The observations presented here are based on a limited project set, though reflect a broad range of soil types and project applications. It is hoped that the data will be continuously augmented in order to develop understanding of the mechanisms of strength development in mixed material.

The mechanisms controlling strength gain in deep columns are better understood (e.g. BRE, 2002) however, the mechanisms controlling the success of mass mixing applications are less well understood. A broader database of soil types, project applications and field & laboratory measurements is needed to develop firm theories and mathematical models of the governing mechanics.

4.2 DEM modelling

The excellent work of Larsson (2003) outlines the state-of-the-art in the understanding of mixing processes for soil mixing applications.

Some recent work by O'Brien (2018) studying the mixing mechanisms using discrete element modelling (DEM) has provided some useful qualitative insight into the mechanisms governing the BRN. The DEM model (see Figure 19) uses particle trace to track individual elements during the mixing process and chart the particle behaviour (see Figure 20). The qualitative conclusions of the study outline how higher BRNs cause cyclical migration of the particles in the plane of rotation about the tool but also laterally paerpendicular to the tool, thus inducing a better quality of mix.

Expansion of such studies is required to develop a numerical framework for both the qualitative & quantitative understanding of mixing mechanisms and to supplement the empirical observations derived from field and laboratory data as highlighted in this paper.

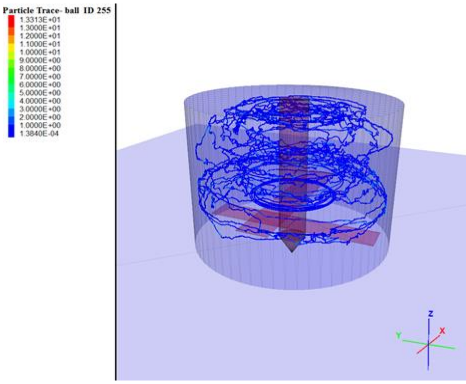

Figure 19. Particle trace during soil mixing using deep column mixing tool

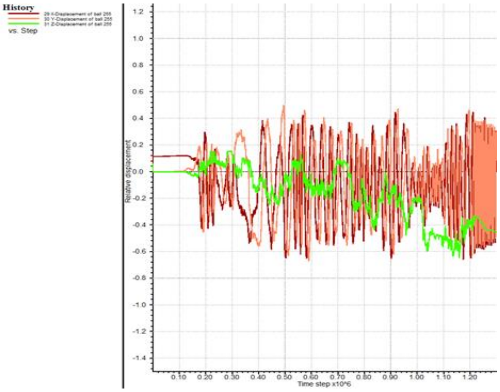

Figure 20. Graphical representation of particle movement during mixing

5 CONCLUSIONS

The results of field & laboratory observations have been presented for both deep column mixing and mass mixing for UK-based projects using wet (grout-based) techniques. For deep column mixing, no discernible correlation was found between sample density & strength. In addition, the development of strength was observed to follow the time-based progression of Åhnberg (2006) well irrespective of whether the native soil was predominantly granular or cohesive.

In terms of mass mixing, mixing time per unit volume has been shown to potentially be a governing parameter in the strength gain progression. Field and laboratory observations suggest that there is an optimal mixing time of between 1.5 and 1.75 minutes per cubic metre of mixed material. It is suggested that this parameter should be used as a control parameter, analogous to the blade rotation number used in deep column mixing, for projects involving mass mixing.

It is noted that there is much scope for further studies particularly around understanding of the mixing mechanisms. Discrete element modelling has shown promise in potentially setting up a numerical framework but further development of field & laboratory databases is also advocated.

6 ACKNOWLEDGEMENTS

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