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IMPACT OF CLAY ON EARLY JET GROUTING STRENGTH

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Jet grouting is a ground improvement technique that has become widely adopted over the past three decades, yet relatively little data has been published about performance characteristics of mixes under adverse conditions, such as the inclusion of clay lenses. This paper presents an experimental investigation on the impact of clay on the strength of jet grouting. A total of 150 grout samples were subjected to 0-10% levels of Kaolinite and Bentonite inclusion. While the Bentonite was introduced as a pre-hydrated slurry, the Kaolinite was mixed in two ways: in a pulverized condition and as large chunks. Sample strength and stiffness were measured at multiple dates within the first 28 days. With 10% clay inclusion all samples exhibited significant strength and stiffness losses. With some substantial losses began with as little as 4% clay inclusion. Even a 1% clay inclusion tended to decrease strength and stiffness between one-quarter and one-third of the control sample. Depending upon clay type and inclusion method, results differed significantly with respect to strength and stiffness development and failure mechanism. Petrographic analysis was used to provide further insights as to apparently divergent behaviors.

INTRODUCTION

Increasingly, jet grouting (a soil stabilization technique) is used for underpinning and retention structures beneath and adjacent to historic buildings and other at-risk structures, yet performance expectations for various jet grouting systems and soil types are not fully documented, particularly for deformability. Documented failures related to unexpected movements of jet grouting have been attributed to initial soil composition (Katzenbach et al. 2003 and O’Rourke and O’Donnell 1997). The influence of the in-situ soil profile on the engineering performance of the hardened material (soilcrete) is not clearly established, especially with respect to clay inclusions. Clay is of particular concern because of its known negative influence on neat grouts, where compressive strength and stiffness is severely reduced by the introduction of small amounts of bentonite (Vipulanandan and Shenoy 1992; Shroff and Shah 1999). Clay may be introduced into the jet grouting through bentonite in the drilling fluid, as well as being encountered as part of the in-situ soil. Clay in the drilling fluid is fluidized and is designed to be hydrated and agitated prior to cement introduction, while in-situ clay is naturally hydrated but not agitated, and thus may be introduced into the jet grouting in relatively large pieces compared to the bentonite. The two scenarios generate distinct cement interactions, yet neither has been rigorously explored. This paper aims to be an initial investigation of this topic.

BACKGROUND

Jet Grouting

Jet grouting utilizes high pressures (typically 300 to 500 bars) to impart energy to a fluid, which is injected into the soil at about 230-330 m/s. (Kauschinger et al., 1992). The resulting “in-situ concrete” is generally referred to as “soilcrete”. Jet grouting was first used by the Japanese in the 1960’s and later adopted widely in Europe and more recently in the United States. There are multiple forms of jet grouting, including single-, double-, and triple-fluid (air, water, and grout). Depending upon the system either the grout or a combination of air and water are used to break up the in-situ soil. In all cases the resulting product can be considered as a “mixed-in-place concrete”; an extensive overview of the basics of jet grouting is provided in Laefer 1997.

There have been many studies conducted on jet grouting soilcrete columns, but the effect of clay on their strength and stiffness has not been thoroughly investigated. Work by Stavridakis (2005) considered the effects of bentonite and kaolinite on the subsequent engineering proper-
ties of cement-improved soil, but most of that work considered mixes with 4-10% cement contents, more typical of deep mixing than jet grouting (Lee et al. 2005), where according to Kauchinger et al. (1992) jet grouting may have cement contents (ratio of the weight of cement to total weight of the mix) of up to 50%. Typical mixes have water/cement ratios of 1:1 by weight (Coulter, 2006 and Burke, 2003) to ensure grout of sufficiently low viscosity to fill up the cut soil volume, allowing air voids to escape (Lee et al. 2005). As part of the jet grouting process many clay types may be encountered. Two common ones are Bentonite and Kaolinite.

**Bentonite**

Bentonite is a sodium clay used in grouting processes because of its water absorption and stabilisation properties allowing lower water/cement (W/C) ratios, which reduces costs.

According to Jefferis (1982) bentonite can be added into grout in one of three ways: pre-hydration of the bentonite prior to introduction, dry mixing of the bentonite and cement with the water added subsequently, and dry cement added to a pre-hydrated bentonite solution. The last one reflects industry practice. Pre-hydration of bentonite typically should take place at least 24 hours prior to mixing followed by agitation from 0 to 24 hours, before addition to the drilling fluid (Burke 2003).

Ball et al. (2006) noted that if 3% or more bentonite powder is dispersed in water, a viscous slurry is formed, which is thick when allowed to stand but thin when agitated. This phenomenon is known as thixotropy and results from the orientation of the plate-like particles within the slurry. When the slurry is allowed to stand, the plate-like particles become oriented in a parallel or semi-parallel manner. Electrical bonding forces between the particles form an interlocking structure, which causes the slurry to gel. When the gel is agitated, the electrical bonds are broken and the slurry becomes fluid. The particles are orientated in a random fashion, which promotes hydration of the bentonite with the water. Full hydration is needed prior to the introduction of the bentonite into the grout to insure homogeneity. Failure to fully pre-hydrate the bentonite generates lumpiness due to the bentonite coating the cement particles (Jefferis 1982).

While bentonite controls bleed and viscosity (Bremen 1997), it can impact final strength. The addition of bentonite to neat grouts has been shown to significantly lower compressive strength. Shroff and Shah (1999) showed a 25% decrease in strength of thick grout mixes and a 50% strength decrease in thin grout mixes of unspecified ages. Vipulanandan and Shenoy (1992) documented a compressive strength loss of 50% through the addition of only 5% bentonite (as a percentage of cement) in a neat grout at 28 days, but the situation is not completely straightforward. In the same study, a grouted sand mix, with an unspecified amount of sand, and small amounts of bentonite generated strength increases of up to 50% over a neat grout, while the compressive strength of the neat grout with 5% bentonite was almost identical to the grouted sand with the same amount of bentonite (Vipulanandan and Shenoy, 1992).

**Kaolinite**

Kaolinite has properties quite distinct from Bentonite. Bell (1976) and Croft (1967) characterized the behavior of bentonite as active (contributing to a reaction with cement), while that of kaolinite as inert. Kaolinite and other well-organized (or well-crystallized) soil minerals appear to have little effect on the hydration of cement and hardening proceeds normally, after short curing periods. In contrast, clay minerals with an expansive lattice (e.g. bentonite) have a profound influence on the hardening of cement and require large amounts of cement, to develop satisfactory strength and durability (Bell, 1976; Croft, 1967).

Kamruzzaman et al. (2006) investigated the micro-structural behavior of cement-treated Singapore marine clay (a form of kaolinite) arising from physico-chemical changes of the clay cement matrix. Mixing of cement into a kaolinite slurry lead to a rapid hydration reaction and the formation of primary cementitious products. Secondary cementitious products were formed following a slower pozzolanic reaction. X-Ray diffraction analysis showed an absence of the kaolinite in the treated soil, although it was part of the original soil matrix. This suggests that the kaolinite chemically reacts with the calcium hydroxide in the cement forming a cementitious material in a pozzolanic reaction, which is consistent with the highly pozzolanic behavior of kaolinite as reported by Eades and Grim (1960). The cementitious material formed in the pozzo-
lic reaction is of a platy reticular structure. Kamruzzaman et al. (2006) looked for the presence of platy reticular cementitious products in scanning electron microscope (SEM) images of the clay-cement matrix as an indicator of long-term strength. The images revealed an uncluttered microstructure, with the platy clay particles assembled in a scattered arrangement. Increasing percentages of cement caused flocculation of the clay particles. The flocculated nature of the structure becomes more evident between 7 and 90 days curing. Stavridakis (2006) confirmed that flocculation is one of the distinct chemical processes that develops the bonds between soil and cement in the cement stabilisation process.

**TESTING PROGRAM**

The test program consisted of 150 samples (10 mixes x 5 test days x 3 samples per day) for unconfined compressive tests and 10 additional specimens for microscopic analysis. The compression tests were carried out at 3, 5, 7, 14, and 28 days using a digimax compression testing machine at a rate of 1mm/min. Displacement was measured using a Linear Variable Differential Transformer.

This project investigated the effects of introducing controlled quantities of clays on soilcrete samples. All samples contained 33% normal Portland cement, 33% water, and a 33% sand-clay mix (Table 1). The variable differentiating the samples was the percentage of clay in the sand-clay mix. This ensured a water:binder content of 1, as recommended by Vipulanandan and Shenoy (1992). The percentages of clays (1%, 4%, and 10%) were selected to give noticeable changes in performance.

Fine Blessington sand was used as the aggregate in this study. Fig. 1 shows its particle distribution. A control mix (S) with no clay was made to benchmark the other samples. This grout was mixed for 15 minutes and then poured into the moulds. This was the general procedure for all grouts once the clay was prepared, except for the chunked Kaolinite, which was manually added to each mold to ensure clay inclusions in each sample.

The bentonite was sourced dry and pre-hydrated 24 hours prior to mixing (Jefferis 1982, Burke 2003), with 100 ml of water added per 100g of bentonite and mixed in a high-speed blender for 2 minutes and then added to a concrete mixer for 15 minutes.

**Table 1: Soilcrete Mix Ingredients**

<table>
<thead>
<tr>
<th>Mix name</th>
<th>Sand (kg)</th>
<th>Cement (kg)</th>
<th>Water (l)</th>
<th>Bentonite (kg)</th>
<th>Kaolinite chunks (kg)</th>
<th>Kaolinite mashed (kg)</th>
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</thead>
<tbody>
<tr>
<td>S</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
<td>BE1</td>
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<td>4</td>
<td>4</td>
<td>0.04</td>
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<tr>
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</tr>
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<td>4</td>
<td>4</td>
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<tr>
<td>KM10</td>
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<td>4</td>
<td>0</td>
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<td>0.4</td>
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S = control sample, B = bentonite, KC = kaolinite chunked, KM = kaolinite mashed, 1, 4, 10 = the percentage of clay in the mixture.

Figure 1. Grain size distribution of sand
In contrast, vacuum-sealed kaolinite was obtained and was kept at a constant, moisture content. The kaolinite was prepared in two different ways: pulverized and chunked. The pulverized kaolinite was prepared by adding a 100ml of water per 100g of clay into a high-speed blender and mixed for five seconds. It was then added to the grout in the mixer. Dissimilarly, the chunked kaolinite was divided into 5g (+/- 0.05g) pieces and added to the grout in stages, while the grout was poured into the molds. Extreme care was taken with the kaolinite to keep it at its natural water content. All solicate samples were cured at room temperature (reflecting industry practice).

Samples were cast in plastic molds 114 mm high with a height to diameter ratio of 2:1 according to D2166-91 in ASTM (1995) [fig. 2]. A small hole was drilled into the end of each mold to facilitate sample removal. This was sealed with duct tape prior to the cement/soil grout mix being poured into the mold. The problem of bleed was overcome by attaching cardboard collars to the top of the molds mostly occurring in the first two hours (Lee et al. 2005). The bleed water was siphoned from the top of the sample and the collar was removed after 24 hours. Excess grout was then shaved from the top of the sample in order to bring the level of the sample to the top of the mould. The sample was then left in the mold for a further 24 hours before being removed. Compression tests were carried out using a testing speed of 1mm per minute.

Figure 2. Freshly Cast and Extracted Samples

Figure 3 shows the top of one of the pulverized kaolinite samples prior to sanding with a pumice stone (to ensure a level, testing surface). The appearance of these samples was similar to the bentonite ones.

In contrast, Figure 4 depicts a chunked kaolinite sample prior to sanding, where the kaolinite is distinctly visible.

Results

Since jet grouting is used for underpinning and retention structures beneath and adjacent to historic buildings and other at-risk structures, there are often very restrictive allowable settlement levels. For this reason, strength and stiffness are the parameters that were selected for examination in this study.

The control sample consistently outperformed all other samples with respect to strength (35KN) and stiffness, even those with only 1% clay inclusion (figures 5 and 6). The control sample (S) was by far the strongest and stiffest sample at all stages, with a 28-day strength of 13.2 MPa and stiffness of 1218 MPa. There was a significant change in stiffness and strength in the control sample between the 7 and 14-day samples, with the 3-day strength only 37% of the 28-day strength. The sample had almost reached it
Figure 5. Average Compressive Strength of All Samples versus Curing Time

Figure 6. Stiffness versus Curing Time
28-day strength after only 14 days (98% of the 28-day strength).

Stiffness increase with the control sample was nearly linear throughout testing (fig. 6). Although this differed from the other specimens, the strength progression for all was nearly indistinguishable for the first seven days. As an example, the 3-day strength of the bentonite samples was 35-40% of its 28-day strength, with strength increasing significantly up to 14 days, after which little additional gain occurred (a maximum of 9% in the subsequent 2 weeks). Interestingly, there was no visible difference between the bentonitic grout and the control grout while mixing. However, the bentonitic grout was noticeably thicker, with much lower bleed levels, once left to settle in the moulds.

The 1% mashed kaolinite sample was only 37% of its 28-day strength at 3 days, but with nearly full stiffness at 7 days. Those with greater percentages of kaolinite may have still been gaining strength as the rate of strength increase stayed constant between the 7-14 day period and the 14-28 day one, thus suggesting that their strength was still increasing after 28 days. Similarly, they showed relatively weak early stiffness. The 10% mashed kaolinite samples had a 3-day strength 24% of the 28-day strength, but reached maximum strength (5.36 MPa) and nearly maximum stiffness (883 MPa) by day 14.

The chunked kaolinite samples were the least consistent with respect to compression strength, despite consistent stiffness performance. The kaolinite chunks appear to have acted as stress concentrators and catalysts for the initiation of failure planes, with the planes often running through the chunks (Figure 7). Consequently the random positioning of the chunks in the samples had a large effect on the results.

On average, when comparing the control sample at 28 days, adding 1% chunked kaolinite decreased strength by 23%, while 1% mashed kaolinite reduced strength by 28%, and 1% bentonite decreased strength by 35%. There are two mechanisms occurring with the bentonite. Initially, bentonite absorbs water lowering the WC ratio, which increase strength and stiffness. Where the bentonite was introduced in larger quantities, especially the 10% level (BE10), the lost water appears to have generated a second mechanism where there is not enough free water for full hydration, thus causing a significant truncation of strength development.

In summary, the addition of small amounts of clay (bentonite or kaolinite) significantly reduced compression strength. Kaolinite could delay strength and stiffness development, while the bentonite showed early gains in stiffness and strength and weaker results at later stages.

Comparison to other published studies proved difficult because of information lacking on either mix percentages or curing times. In a gross sense the results by Fang et al. (1994) on a form of kaolinite was highly similar, but the bentonite mixes by Vipulanandan and Shenoy (1992) were much stronger. To better understand how the various mixture components interacted, SEM images were taken of many of the samples (e.g. Figure 8). Despite reference images being available through Welton’s SEM Petrology Atlas (1984) for kaolinite and bentonite particles, trends were difficult to identify, and quantification proved untenable. Arguably, the most that could be said was that flocculated clusters and reticulated cement-clay structures were present in both the bentonite and kaolinite samples. As an alternative, thin sections of each mix were made after 28 days. These were ground to a few microns in thickness and affixed to a glass slide to view the microstructure (Figures 9-15).
Figure 9. Microscopic Image: Sand-Cement Control Sample

Figure 10. Microscopic Image: Bentonite Sample (Bentonite circled)

Figure 11. Close up of Bentonite Figure 10

The control sample (Figure 9) and that with bentonite (Figures 10 and 11) appear largely indistinguishable, except for the visible bentonite pieces which show as blue or yellow depending upon refraction characteristics. The mashed kaolinite (Figure 12) took on a different visual aspect with pieces of kaolinite highly distinguishable and with identifiable boundaries.

Figure 12. Microscopic Image: Mashed Kaolinite 10% (KM10)

Figure 13. Close-up of Mashed Kaolinite (Figure 12)

Despite pulverization, the kaolinite did not completely disperse. The darker shade in the centre of the kaolinite chunk (Figure 13) indicates a higher concentration of the clay, while the lighter, outer section of the chunk suggests a chemical reaction between the kaolinite and the surrounding cement and sand. This observation is consistent with the findings of Kamruzzaman and associates (2006) who found that the kaolinite clay minerals found in Singapore marine clay were sufficiently active in generating a pozzolanic reaction that they often thoroughly exhausted from the cement treated sample. The kaolinite seems to be propagating outwards into the soil cement matrix, which indicates some form of fluidity within. This can be explained, as it takes longer for water to dissipate from the clay than the surrounding sand and cement, thus water escapes from the chunk at a slower rate and promotes the reaction between the kaolinite and its surroundings. The pozzolanic reaction may explain the steady increase in latter strength of the chunked and mashed samples.
relative to the bentonite samples of the same percentage clays.

Figure 14. Microscopic image: Boundary between Kaolinite Chunk and Surrounding Soil-Cement Matrix

Figure 15. Close up of Kaolinite Chunk (Figure 14).

Implications for Practice

Since a major application of jet grouting is beneath historic structures, where rapid load transfer is desirable, Figure 16 was devised. The goal was to begin to sense whether the loss of stiffness due to clay inclusions does or does not pose a potential, unexpected risk for historic buildings. Using conservative assumptions about foundation capacities for early 20\textsuperscript{th} century structures in most of America’s major turn-of-the-century cities would lead to the presumption of foundation widths twice the thickness of the ground floor walls made of medium hard brick in a lime mortar resulting in an upper bound of 10\textsuperscript{MPa}, with values of half more typical and those on the west coast less strong than those in the east (Laefer 2008). As such Figure 16 was constructed for a “worst case scenario” of 6 m long soilcrete columns, where applied stress would generally be in the range of 5\textsuperscript{MPa} along a building’s shallow footing.

The loads were considered against pre-established settlement limits that have been used for structures displacing under self-weight (as opposed to differential settlement), namely Wong and Poh (2000), Terzaghi and Peck (1943), and Skempton and McDonald (1956). The Skempton and McDonald allowable limit of 50 mm is arguably the most widely adopted for self-weight, but in the case of historic or at-risk structures 10-15 mm is more common. Based on this more restrictive limit, potential settlement problems arose at loadings as little as 1000 kN for mixes containing 1\% and 4\% clay and at 500 kN for those with 10\% kaolinite. However, in most cases there were no problems. Mixes without any clay could withstand loads up to 2500 kN without any risk of significant settlement. Had the soilcrete columns been shorter than the quite long ones of 6 m that were selected the settlement would have been more manageable, even under greater loads without any risk to the structures. Wider columns are also a possible solution.

Further work in this area is clearly needed. In particular understanding strength and stiffness development with the first 28 days and using more advanced and quantitative techniques to examine the soilcrete composition.

CONCLUSIONS

Even small amounts of clay considerably reduced the soilcrete strength and stiffness. Particularly the following conclusions can be drawn:

- Bentonite compromised later stiffness, while the mashed and chunked kaolinite samples were slow to gain stiffness but by 28-days were almost indistinguishable from the control samples.
- Depending upon the clay and the introduction method, significant strength loss began at as little as 4\% clay inclusion and was pronounced in all samples with 10\%.
- Water dissipated from the kaolinite (at its natural water content) more slowly than it was consumed by the hydration process in the surrounding sand-cement matrix, thus, causing probable significant further hardening beyond the 28-day testing program.
• Chunks of kaolinite caused local stiffness changes, which ultimately served as points of stress concentration and points of weakness in the soilcrete matrix.

• Under sufficient compression, fracture occurred along the plane with the highest concentration of kaolinite chunks.

• Early strength and stiffness results could not be consistently extrapolated to accurately predict a 28-day performance, even within a particular clay type and processing technique.

• Despite significant strength and stiffness losses due to even small amounts of clay inclusion the implications for practice are relatively modest, with damage occurring only with quite long soilcrete columns under fairly highly loaded historic building foundations.

**References**


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Figure 16. Potential settlement of 6m long jet grouted columns beneath historic buildings


