

Utilization of Industrial by-products in Ground Improvement Applications

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ABSTRACT

With technological advances in ground improvement equipment, in-situ deep mixing is considered as a fast method of ground improvement. However, the financial cost of high cement dosage along with carbon footprint of chemical stabilization using Portland cement restrains the widespread use of this technology. Ground granulated slag and class F fly ash are examples of under-utilized waste powders that are rich in Alumina, silica and calcium. Alkaline silicate and hydroxide solutions have been used to produce Aluminosilicate gel along with C-S-H gels at room temperature and create strength characteristics similar and even higher to that of Portland cement stabilized specimens. Utilization of industrial by-products such as slag and fly ash not only redirects these by-products from landfills but also can improve the sustainability of the construction projects. In addition, the financial benefits of replacing Portland cement with alternative low-cost binders can encourage the contractors to utilize these waste materials. This research investigates differences in the rheology and microstructure of the stabilized loose sand and silty clays with alkali-activated slag and fly ash and provides insights into differences in stabilization techniques in sandy and clayey deposits. The moisture sensitivity, binder dosage, particle size, porosity and curing condition for stabilized materials are compared between the two parent materials. Additionally, in order to understand decementation in the smear zone surrounding the treated soilcrete column, the shear wave velocity was used to correlate the deterioration of bonds between the soilcrete and the surrounding soil with stress level. A one-dimensional consolidation cell was used to measure the changes of shear velocity and porosity of lightly stabilized samples, representing the materials in the smear zone, under different confinements at k_0 loading to recognize the rapid drop of shear velocity as a sign of decementation in early failure stages. This investigation provides a deeper insight into soil-cement interaction in a range from treated soilcrete column to the smear zone transforming the load to the surrounding soil by optimization of binder content, speed of mixing, adapting to the natural moisture content which in turn increases the level of confidence in utilizing this quick method of ground improvement with sustainable materials.

RÉSUMÉ

Avec le progrès technologiques des équipements d'amélioration géotechnique des sols, le malaxage profond in situ est considéré comme une méthode rapide d'amélioration des sols. Cependant, le coût financier d'un dosage élevé de ciment ainsi que l'empreinte carbone de la stabilisation chimique à l'aide de ciment Portland limitent l'utilisation généralisée de cette technologie. Le laitier broyé et les cendres volantes de classe F sont des exemples de sous-produits riches en alumine, silice et calcium. Des solutions alcalines de silicate et d'hydroxyde ont été utilisées pour produire un gel d'aluminosilicate avec des gels C-S-H à température ambiante et créer des caractéristiques de résistance similaires et même supérieures à celles des échantillons stabilisés au ciment Portland. L'utilisation de sous-produits industriels tels que les scories et les cendres volantes permette de valoriser ces sous-produits, mais peut également contribuer à la durabilité des projets de construction. De plus, les avantages financiers du remplacement du ciment Portland par des liants alternatifs à faible coût peuvent encourager les entrepreneurs à utiliser ces sous-produits. Cette recherche étudie les différences dans la rhéologie et la microstructure du sable meuble stabilisé et des argiles limoneuses avec des scories et des cendres volantes activées par un alcali et donne un aperçu des différences dans les techniques de stabilisation des dépôts sableux et argileux. La sensibilité à l'humidité, le dosage du liant, la taille des particules, la porosité et les conditions de durcissement des matériaux stabilisés sont comparés entre les deux matériaux parents. De plus, afin de comprendre le phénomène de désolidarisation du ciment dans la zone entourant la colonne de sol en béton traité, la vitesse des ondes de cisaillement a été utilisée pour corréler la détérioration des liaisons entre le massif en béton et le sol environnant sous contrainte. Une cellule de consolidation unidimensionnelle a été utilisée pour mesurer les changements de vitesse de cisaillement et de porosité d'échantillons légèrement stabilisés, représentant les matériaux dans la zone de frottis, sous différents confinements au chargement k_0 pour reconnaître la chute rapide de la vitesse de cisaillement comme signe de désolidarisation du ciment dans premiers stades de défaillance. Cette enquête fournit un aperçu plus approfondi de l'interaction sol-ciment dans une gamme allant de la colonne de sol en béton traité à la zone de frottis transformant la charge sur le sol environnant en optimisant la teneur en liant, la vitesse de mélange, en s'adaptant à la teneur en humidité naturelle qui à son tour augmente le niveau de confiance dans l'utilisation de cette méthode rapide d'amélioration du sol avec des matériaux durables.

1 INTRODUCTION

The growing demand for construction on coastal areas and river deltas as major cities and business districts has

resulted in the construction of high rise buildings and consequently requires improved foundation solutions. These cities are often located on deep layers of compressible soft marine clays or loose sand and silt that

construction end-bearing piling systems are often costly or impractical. The Melbourne central business district is partially located on the Yarra Delta that includes formations such as Port Melbourne Sand (QP) and Coode Island Silt (Qc) with an undrained shear strength of 15 – 30 kPa followed by stiffer lower strata of Fishermens Bend Silt (Qf) and Moray Street Gravels (Qm) with a shear strength of up to 80 kPa [1] that extends to 30 m or more [2]. The alternative ground improvement techniques are dependent on costly and unsustainable use of Portland cement.

These methods are often used to increase the shear strength in a soil mass for improving the friction with the structural element or used as a concentrated mixing to create soilcrete piles with higher compressional strength compared to the surrounding soil. The high stiffness of structural elements such as precast concrete piles or steel elements will lead to absorbing the majority of the stresses which in turn causes the concentration of stress and strain and detachment of the structural element from the surrounding soil. Many researchers are trying to determine the optimum blend of grout constituents and also moisture content to account for acceptable mixing and maximum compressional and shear strength using Portland cement [3, 4]. Industrial by-products which are rich in silica and alumina and calcium are a sustainable alternative that can significantly reduce the environmental burden of ground inclusion projects by eliminating the use of Portland cement reducing the carbon footprint to a minimum [5].

Generally, the high moisture content of the soil in ground inclusion techniques such as deep soil mixing, demand high content of binders which in turn reduces the flowability of the grout and increases the capacity and power of pumps. The strength of the stabilized soil is highly dependent on the moisture content of the mix as demonstrated by Mohammadinia et al. [6]. The strength can, however, be managed by controlling the number of passes or changing the viscosity of the grout with elevation [7]. The surrounding area of the mixed column in cohesive soils are highly disturbed and can gradually create cement bond and cohesive interaction with the soilcrete. However, this interaction is weak and marginal in sandy soil due to relatively high permeability which leads to leaching the grout away from the soilcrete and also lack of cohesion in the parent soil.

In this research, the optimization of the use of alkali-activated fly ash (FA) and slag (S) as low-carbon alternatives to Portland cement for stabilization of loose deposits was reviewed and the relation between the critical stress level and shear wave velocity at smear zone surrounding the stabilized soilcrete was investigated.

2 MATERIALS AND METHOD

2.1 Materials

A typical Clayey Silt, know as Coode Island Silt (CIS) and also a relatively uniform fine Sand was collected from a local cut for a construction site in the central business district at Melbourne, Victoria. CIS with $D_{max} = 0.15$ mm, $G_s = 2.61$ and a natural moisture content of 45% – 60% was highly plastic ($PI = 27.0$) while sand with a $D_{max} = 0.85$ mm,

$G_s = 2.65$ was non-plastic with a natural moisture content of 20% - 25% (Fig 1).

The chemical compositions of the class F fly ash and slag used in this research are compared with Portland cement in Table 1. The commercially available fly ash also known as Melbourne Ash was a blend of Gladstone and Callide Ash that is the down-stream by-product of burning black coal. The local commercially available ground granulated blast furnace slag was sourced for this research. Alkaline solutions have been used to increase the reaction rate in a higher pH environment. Although alkaline solutions such as potassium silicate and hydroxide have been successfully used in stabilization of loose sand and silts, sodium silicate and hydroxide have been more efficient in these applications [8]. Sodium hydroxide beads were used to prepare NaOH solution with 8M concentration to avoid any safety breaches during the sample preparation and by extension during the construction. In addition, the premixed Grade D sodium silicate solution (Na_2SiO_3) was used.

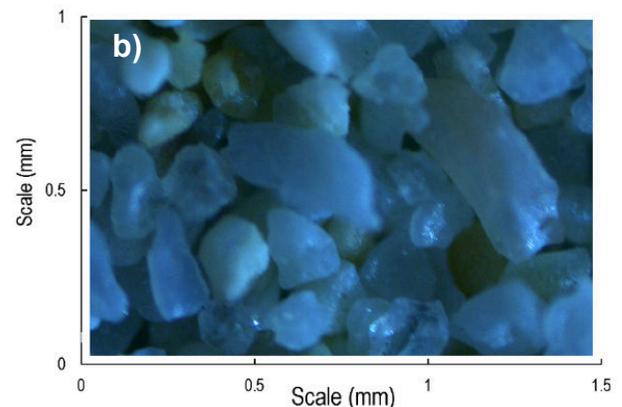
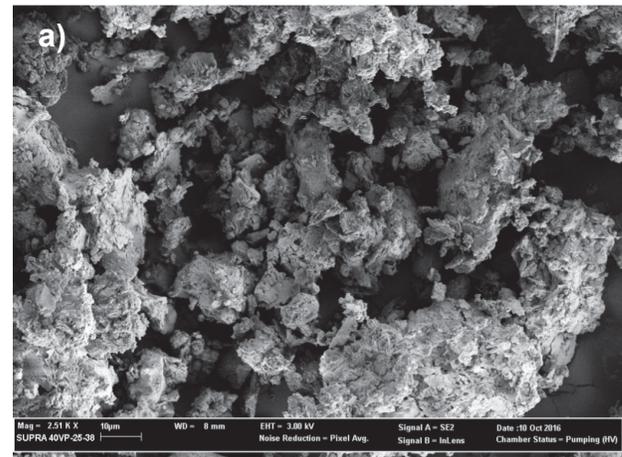


Figure 1. a) SEM image of CIS [8] and b) microscopic image of fine sand [9]

The design criteria are often considering a unconfined compression strength (UCS) of 700 kPa for the deep mixed soils [4]. However, in-field practitioners target the mix-design to gain a strength of at least 2 MPa [9]. Both sand and CIS was mixed with additive percentage of 10, 20 and 30% by dry weight of parent soil with equal parts of slag and fly ash (i.e. FA:S = 50:50).

Table 1. Chemical composition of Portland cement and FA

Chemical	Portland cement (wt.%)	Fly ash (wt.%)	Slag (wt.%)
AL ₂ O ₃	4.5	25.56	13.8
SiO ₂	20.3	51.11	34.2
CaO	62.9	4.3	43.1
Fe ₂ O ₃	4.6	12.48	0.4
K ₂ O	0.3	0.7	0.4
MgO	1.2	1.45	5.4
Na ₂ O	0.3	0.77	0.1
SO ₃	2.6	0.24	0.8
Loj [§]	3.3	0.57	1.8

[§]Loss on ignition

2.2 Compressional strength

The sand was then mixed at its optimum moisture content provided from proctor test at standard energy and CIS was mixed at its liquid limit to replicate the field conditions. The alkaline activator was prepared with equal parts of sodium silicate and sodium hydroxide and was mixed with the dry blend at alkaline liquid (L) to precursor (P) ration of 1.0. The mix was moulded in cylindrical tubes of 38 mm in diameter and a 76 ± 2 mm in height. The average value of three identical samples was reported as the UCS value (Fig 2).

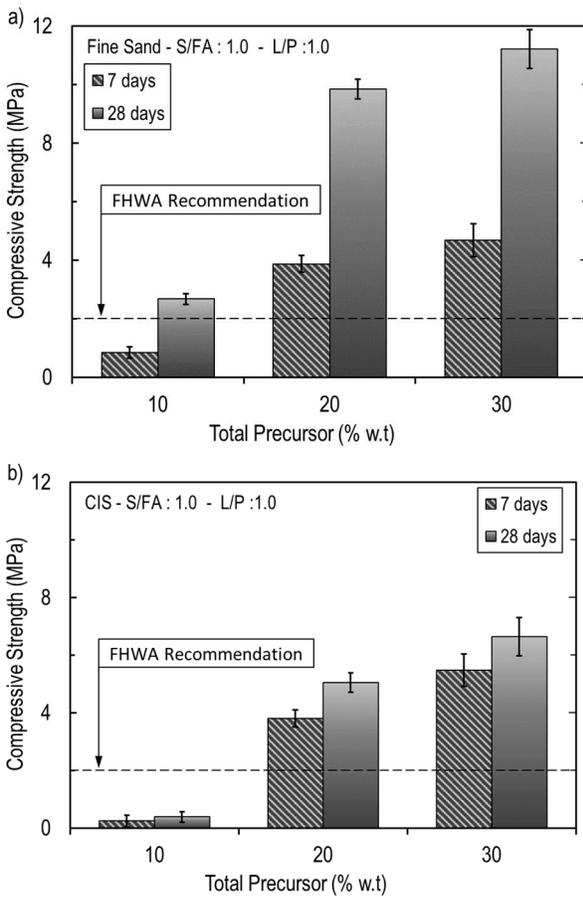


Figure 2. Strength development of alkali-activated a) fine sand and b) CIS modified after [9, 10]

Although 10% additive increased the minimal to non-existing strength of the parent soil to a relatively high strength of 300 – 700 kPa, it was not enough to create a homogeneous network of binder gels to increase the load-bearing of the samples. The significant surge in strength by increasing the binder content to 20% was noticeable followed by a moderate improvement in strength when the binder content was increased to 30%.

1.1 Behaviour of smear zone

The leachate of the alkaline grout and cement to the surrounding soil and its interaction with the soilcrete has been of researchers interest [11, 12] particularly for loose sands. In this research, a non-destructive test was selected to study the debonding of the slightly stabilized aggregates. The materials softening under K_0 loading was modelled in a one-dimensional compression cell which was equipped with bender elements at top loading platen and bottom of the cell that was constantly measuring the shear wave velocity of the sample.

The basic theory of the relation between the stiffness of soil skeleton (E_{esk}) and the stiffness of the binder (E_{bin}) and the mean stress level is controlling the speed of shear waves through a soil mass [13, 14] was used to characterize the debonding of cementation and correlate it to the settlement measured at the top platen.

A solid thick-wall cell was fabricated with fittings for bender element at top and bottom to replicate the K_0 loading conditions (Fig. 3). The bender elements were grounded to minimize the cross-talk between the cell walls and bender elements [15].

RIGOL DG1022 was used to generate the sinusoidal input signals with a frequency of 2kHz. The input signal transmitted simultaneously through to bottom bender element and also to the oscilloscope with a sampling rate of 400 kHz which was then digitized and collected in a computer. The time difference in the first peak between the input and received signals was then calculated as the travel time. The travel distance in each stage of loading was also updated with LVDT measurement of settlement in each stage and was subsequently used for calculation of shear wave velocity (v_s). 2% of stabilization was chosen as the lightly stabilization based on the recommendation of Yun and Santamarina [13].

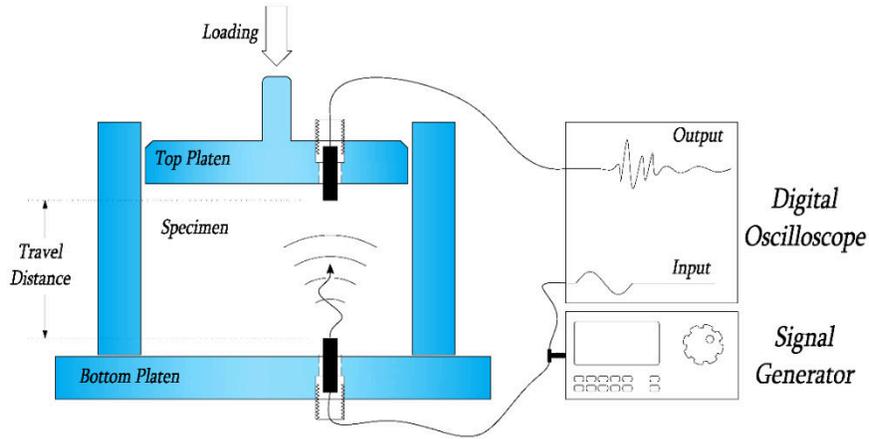


Figure 3. Oedometer cell setup with bender elements fittings

The changes in shear wave velocity is compared between the loose sand, 2% Portland cement stabilized sand and 2% FA/S stabilized sand in Fig. 4. The loose unbound sand is presenting a linear behaviour during loading/unloading that confirms the Hardin contact model. In the other hand, both of the stabilized samples have experienced a drop starting at mean stress of 100 kPa showing the starting

process of decementation which continued up to 300 kPa of pressure during which the maximum amount of settlement was recorded at the top platen. This was followed by the increase in the shear velocity due to rearrangement of particles and forming more particular contacts with similar steepness to that of unbound sand.

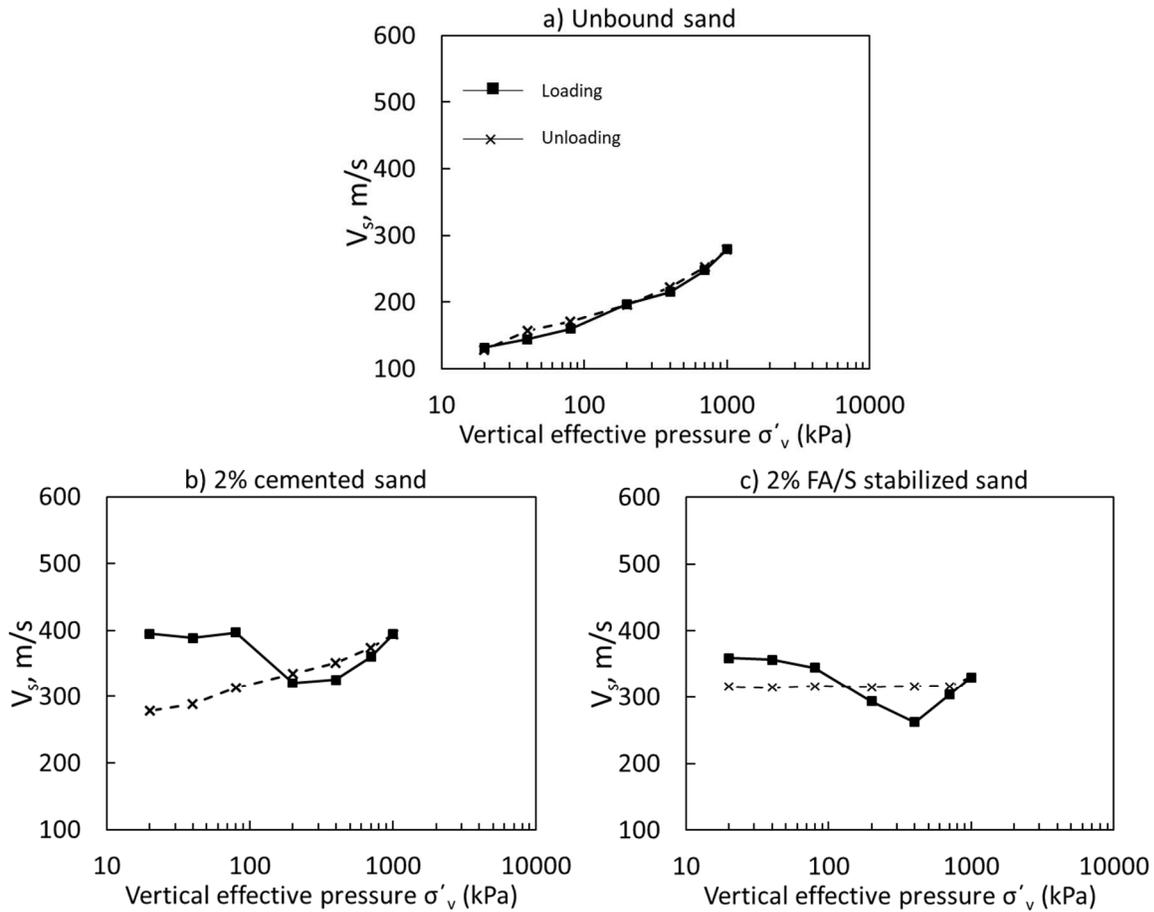


Figure 4. Change in shear wave velocity vs during loading/unloading sequence of one-dimensional compression test

3 DISCUSSIONS

The strength sensitivity of these blends to the variation in the natural moisture content of the soil is less compared to Portland cement. Although the design charts often specify usage of up to 150 kg/m³ of cement in the deep mixing application, there is often need of a second pass due to high natural moisture content, particularly under the groundwater table. However, the alkali-activated mixes with the combination of slag and fly ash are less sensitive to moisture variations.

In addition to the financial and environmental benefits of the use of industrial by-products, the behaviour of the slightly stabilized smear zone surrounding the soilcrete is fairly similar between the alkali-activated by-products and cement stabilized soil. The loose deposits are often too deep that creating piles with end bearing is often too costly and/or not achievable. In these cases, the suspension pile elements are designed to high levels of strength but more for transforming the load to the loose deposit. Hence, the load transformation from the surface structure into the soilcrete and ultimately to the surrounding loose deposit is highly dependent on the interaction of the soilcrete and the loose surrounding soil. The stiff nature of Portland cement gels is creating a stress concentration due to large difference in stiffness and hence strains which can lead into several local failures accumulated to detachment of the entire pile element from the supporting foundation.

5. CONCLUSION

The calcium-rich slag and alumina and silica-rich fly ash are cheap and sustainable replacement for Portland cement that can generate similar compressional strength when mixed with loose sand and soft clays at a slightly higher dosage. The characterization of the decementation in relation to changes in void ratio and shear velocity in the soil can enlighten the trend of failure in the smear zone and can be utilized for modelling the interaction between the structural stabilized pile element and the loose surrounding soil.

6. ACKNOLEGMENT

The authors would like to acknowledge the University of Melbourne and Dr.Mahdi Miri Disfani for their support and Florence Damour for translation of the abstract.

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