Cyclic Wetting and Drying Behaviour of Coal Wash Treated Black Soil

Courage Kwasi Dzaklo,[1] Cholachat Rujikiatkamjorn, PhD., M.ASCE[2], Buddhima Indraratna, Ph.D., F.ASCE[3], and Richard Kelly, Ph.D.,[4]

[1]PhD Candidate, School of Civil & Environmental Engineering, University of Technology Sydney, NSW 2007., ARC Industrial Transformation Training Centre (ITTC-Rail), University of Wollongong, Wollongong, NSW 2522, Australia. Email: Courage.K.Dzaklo@student.uts.edu.au

[2]Professor, Transport Research Centre, University of Technology Sydney, NSW, 2007, Australia., Email: cholachat.rujikiatkamjorn@uts.edu.au

[3] Distinguished Professor and Director of Transport Research Centre, University of Technology Sydney, NSW, 2007, Australia., Email: buddhima.indraratna@uts.edu.au

[4]Conjoint Professor of Practice, University of Newcastle, University Drive, Callaghan, NSW,2308, Australia., Chief Technical Principal and General Manager, Technical Excellence, SMEC, Brisbane, QLD, Australia., Email: DrRichard.Kelly@smec.com

ABSTRACT

The abundance of granular waste materials coupled with their successful reuse in construction fills has provided sustainable alternatives to a rather expensive quarried natural rock aggregate. This study focuses on the application of coal wash (CW) as an admixture to mitigate the undesirable shrink and swell characteristics of expansive black soils under unconfined compression loading. CW is a by-product of the coal industry that requires an enormous area of landfill for storage. These landfills pose a serious environmental problem because coal is still being produced in many parts of the world. A series of unconfined compression tests were conducted on CW-Soil mixtures with and without wet and dry cycles; these wet and dry cycles mimic the shrink and swell characteristics of expansive soil observed in the field. Our findings show that cracking and shrinking impact the fabric of CW-Soil over time, which reduces their shear strength. The incorporation of CW into black soil reduces its susceptibility to shrinkage and swelling during wet and dry cycles. The relationship between the shear strength reduction after repeated wetting and drying are proposed for consideration in the design. The study shows that the addition of CW can improve the geotechnical properties of expansive soils under unconfined compression and curtail the degradation of the areas used to store the CW.

Keywords:

Coal wash, Black soils, Wet-dry cycles, Swell pressure, Shrinkage, Cracking

INTRODUCTION

Black soils are expansive clays that are susceptible to cracking and swelling after drying and wetting. These soils are referred to as vertosols based on the Australian Soil Classification System (ASCS) (Mckenzie, 1998). The shrink and swell behaviors of black soil have numerous undesirable effects on the above-ground structures which limits their use as foundations. Since expansive soils are ubiquitous on every continent, the damage they cause adds up to billions of dollars (Nelson and Miller, 1997). Osman et al. (2005) reported there was $150 million of damage annually between 2004 and 2009 associated with expansive soils in the state of Victoria, Australia. The estimated maintenance cost of a railway built on expansive soils is twice as much as railways built on rock foundations (Department of transport and regional services, 2007). Moreover, expansive soils can compromise the safety and stability of gas pipelines because soil movement can cause non-uniform stress concentrations along the pipe, which lead to bending and fatigue.

Different ground improvement methods, including the use of cement, lime and fly ash (Firoozi et al., 2017, Alazigha et al., 2018), have been proposed and tested to alleviate the movement of expansive soils by focusing on reducing the degree of swelling and shrinkage that generates uplifts and cracks. This study, however, focuses on the use of CW to reduce the volumetric change and improve the shear strength of expansive soils as an environmentally friendly alternative. The findings include a series of wetting and drying tests, unconfined compression tests, and basic geotechnical tests.

MATERIALS AND TESTING METHODS

Materials: The expansive soil used in this study was sourced from New South Wales (NSW), Australia, from a depth of 2 metres under a railway line. The liquid limit and plasticity index of the oven-dried soil were 85% and 51% respectively. These parameters classify the soil as high plastic soil based on the Unified Soil Classification System (USCS) with a specific gravity of 2.64. The particle size distribution carried out according to ASTM D1140-17 (2017) and the swell percent of natural soil are shown in Figure 1. The swell percent of 6.8% classified this natural soil as high expansive soil based on the classification scheme proposed by Seed et al. (1962).

The coal wash (CW) used in this study came from Illawarra Metallurgical Coal, NSW, Australia. CW is produced as coal is washed to remove impurities such as sulphur, before being used in power plants. The particle size distribution of the coal wash shown in Figure 1a, varies from 75 μm to 9.5 mm. The CW particles consist mainly of quartz, kaolinite, illite, and residual coal. This CW is mostly sand-size particles with lower specific gravity than black soil. Based on the Unified Soil Classification System (USCS), this CW could be classified as well-graded sand with silt (SP-SM).

Testing Methods: Pulverized expansive soil and the selected range of CW were mixed to form different particle size distributions with an increasing amount of CW by dry weight. The proportion of CW ranged from 0% to 50%. The CW-Soil mixtures were sieved through 425-µm sieve following ASTM D4318-05 (2005) for the Atterberg limits and linear shrinkage tests. To determine the swelling pressure and conduct unconfined compression tests, air-dried expansive soil and CW were mixed with a predetermined amount of water and kept in a humidity-controlled room for at least 24 hours before being compacted. Sridharan and Sivapullaiah (2005) proposed a mini compaction approach, which was adopted to study the influence of CW on expansive soil. This technique produced results similar to the standard Proctor compaction approach listed in ASTM D698 (2000).

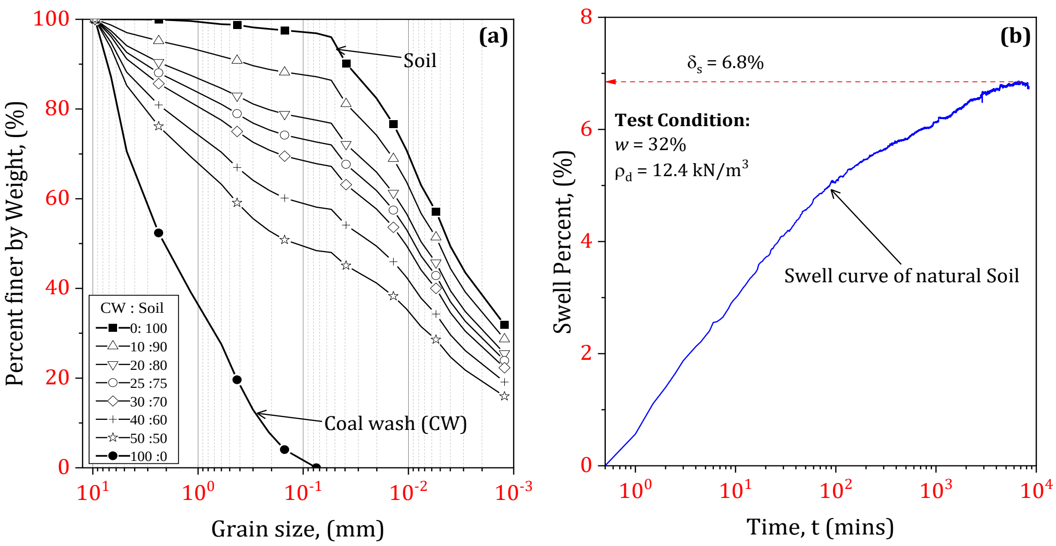

Figure 1. (a) Particle size distribution of soil and coal wash (CW), (b) Swell percent curve of natural soil.

The swelling pressure specimens were compacted to their maximum dry density (MDD) and optimum moisture content (OMC) obtained from the compaction results reported by Dzaklo et al. (2021). The specimens were 50 mm in diameter and 20 mm thick. The specimens were transferred into modified one-dimensional consolidation cells fixed with load cells to record upward loads. The load readings were converted into swell pressure values during the data analysis and interpretation stages. An upper limit of 30% CW because Kaliboullah et al. (2015) show that CW particles have the potential to break upon the application of external loading, which is further exacerbated by the cyclic change of moisture (i.e. wetting and drying cycles) and increased amount of CW content. Dzaklo et al. (2021) has also demonstrated that treated soil with 40% - 50% CW experienced notably high breakage indices (>8%) and such extent of particle degradation can compromise the overall long-term performance of the blended matrix. In addition, it is difficult to control the moisture content for 40%-50% CW specimens during compaction as these samples were very brittle.

The unconfined compression specimens were 50 mm in diameter and 100 mm thick. Dzaklo et al. (2021) reported a negligible scale effect of coarser particle sizes relative to the compaction mould. These compacted specimens underwent drying in an oven kept at a constant temperature of 38°C until there was no change in their mass. Their mass and reduced dimensions, as well as any physical observations such as cracks, were recorded. The dried specimens were then transferred into a 50 mm inside diameter by 150 mm high acrylic tube. The tube had 1 mm diameter holes drilled along the sides in two sets of diametrically opposite points. Four vertical filter papers were placed over the holes inside the tube to allow for the radial drainage of water. Porous stone and filter paper were then placed at the top and bottom of the specimens. The specimen was fully immersed in water and monitored for any increase in size and mass. The fully wetted specimen was then removed and its mass and external dimensions were measured; this completed the first wetting and drying cycle (W-D cycle). This process was repeated until the desired number of W-D cycles was attained. The specimens were extracted from the tubes and placed between the loading cell and pedestal of the unconfined compression rig. An upward loading rate at 1 mm/min was applied until the specimen fails.

TEST RESULTS AND DISCUSSION

Atterberg Limits: The influence of CW on the Atterberg limits of the expansive black soil is shown in Figure 2. The findings indicate a general reduction in all the consistency limits under consideration as the amount of CW increased. The relationship between the plasticity index and the liquid limit of CW treated soils follows a trend of monotonic reduction that is represented by the linear equation shown in Figure 2. The addition of 30% CW reduced the liquid limit, the plastic limit, and the plasticity index by 23%, 26%, and 21% respectively. All the specimens tested, apart from those with 50% CW plotted in the CH region (i.e., high plasticity clay) based on the USCS. The addition of 50% CW to the expansive soil pushed the mixture into the CL region (i.e., low plasticity clay). A similar rate of reduction in the consistency limit was reported by Ma et al. (2021) and Jung and Santagata (2014) on expansive soil treated with coal gangue and coal mine waste in combination with other additives to treat expansive soils. This behaviour can be attributed to the continuous reduction in the portion of clay-sized particles which influenced the consistency limits.

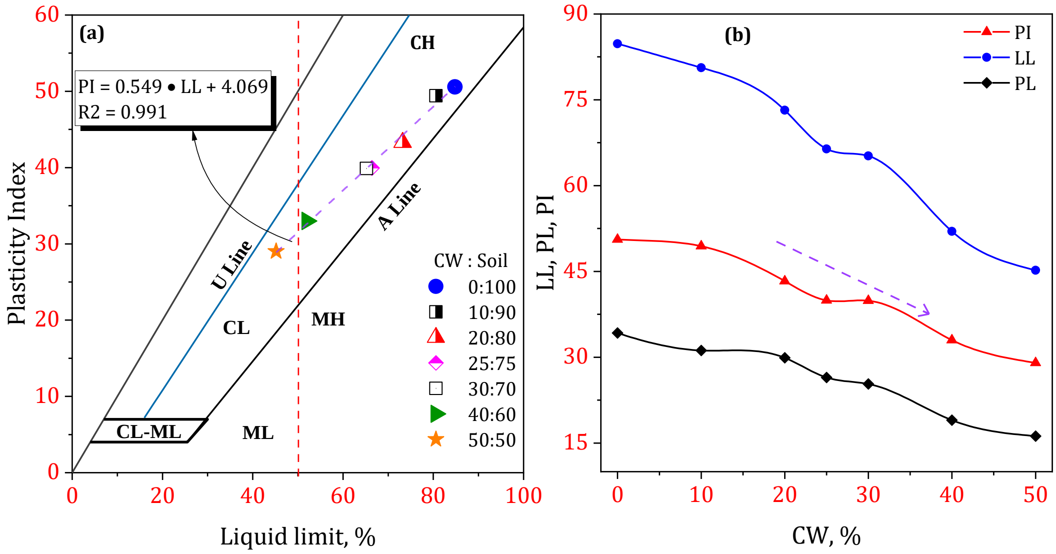

Figure 2. The effect of coal wash on the Atterberg limits of soil: (a) plasticity chart of CW-Soil mixtures, and (b) reduction of Atterberg limits with coal wash.

Swell Pressure: Swell pressure measurements are pivotal in the study of the uplift potential of expansive soils. The impact of CW on the swelling pressure of expansive soil is shown in Figure 3. The Figure shows a linear reduction in swell pressure as the amount of CW increases. The swelling pressure of natural soil is 43 kPa, which is higher than the expected minimum overburden and wheel load stresses on subgrade materials (Ferreira et al., 2011). With 30% CW, the swell pressure of natural soil decreased to 15 kPa, which is a 36% reduction, as shown in Figure 3. Approximately 30%CW was assessed as the optimum amount of CW to be added to expansive in a previous paper published by the authors (Dzaklo et al. (2021). The density of the mixtures increases with the amount of CW, and the moisture content decreases because the swelling pressure has a direct relationship with the overall amount of clay minerals. The proportion of clay minerals in the expansive soil were reported by (Dzaklo et al. (2021). Moreover, CW particles serve as discontinuities in the clay soil structure which prevent continuous swelling.

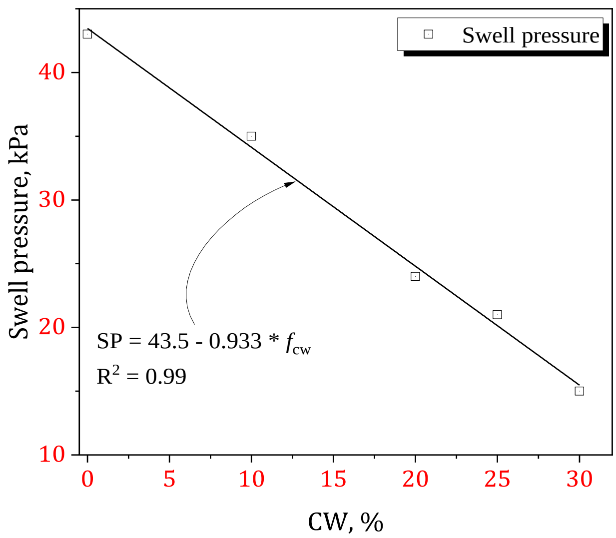

Figure 3. Variation of swell pressure with the amount of coal wash.

Unconfined Compression Strength Tests: The stress-strain curves of natural and expansive soils treated with 30% CW obtained from unconfined compression tests under different wetting and drying cycles (W-D cycles), are shown in Figure 4. These tests were carried out to assess the effectiveness of expansive soils treated with CW under the alternating wetting and drying phenomena observed in the field. The peak stress of naturally compacted soil was 204 kPa at an axial strain of 5.4%. However, with the addition of 30% CW, the mixture attained a peak stress of 320.9 kPa, which is 57% higher than the natural soil. However, the addition of CW slightly reduced the ductile behaviour of natural soil, whereas the unconfined compressive strength generally decreases as the number of W-D cycles increases. The first W-D cycle significantly reduced the peak stresses of both natural and CW-treated soil; the peak stresses were 106.5 kPa and 228.9 kPa, which is a 48% and 29% reduction in peak strength, respectively. This significant reduction in strength at the end of the first W-D cycle is associated with the large volumetric change recorded, but as the number of W-D cycles increases, the rate of volumetric change decreases and hence there was less impact on the strength of the specimens. The mixture of CW and expansive clay under unconfined compression tests resulted in higher unconfined shear strength values because a modified gradation (well-graded) and improved MDD was achieved. The fine-grained particles from the soil filled the voids created by the CW particles to provide better interlock. This led to a well compacted mixture with increased MDD under similar compaction effort. The higher strength was due to the frictional resistance between the soil and CW particles which otherwise did not exist before. Moreover, the mechanical interlock between the CW particles and soil grains prevents the particles from slipping easily during shearing, which leads to higher peak stresses. There may be an unknown chemical reaction between CW and soil which can be investigated in the future. However, this is beyond the scope of the paper.

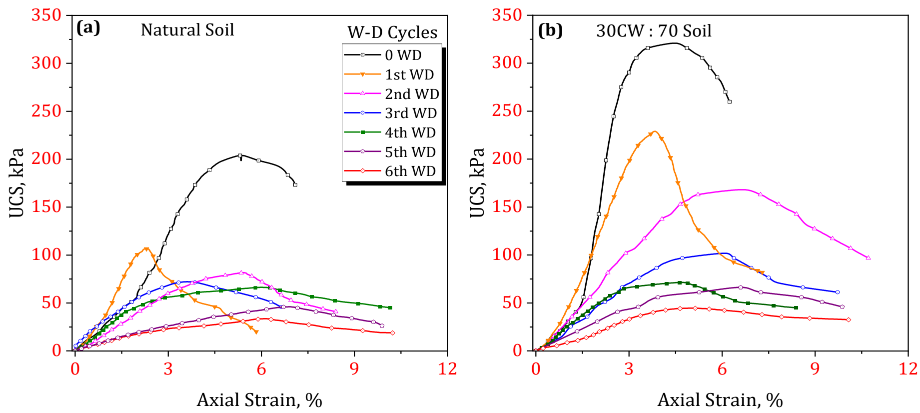

Figure 4. Effect of wetting and drying cycles on stress-strain characteristics of natural and CW treated expansive soil.

Wetting and Drying Cycle: The natural phenomenon of annual wet and dry weather changes were explored to study the deformation of natural and CW treated expansive soils. The influence of CW on the axial deformation of compacted natural and CW-treated specimens is shown in Figure 6. There was a higher overall axial deformation in the natural specimen than in the CW-treated soil. The volumetric changes plateau within 3-4 W-D cycles, as observed by Wang and Wei (2015) and Estabragh et al. (2015). The maximum axial deformation at the end of the 6th W-D cycle was 8.1% and 2.8% for the natural and CW-treated specimens respectively. This indicates that soil destruction is very high in untreated soil. This is confirmed by the developed crack patterns at the end of the 4th W-D cycle as shown in Figure 5. The natural soil developed larger crack openings relative to the smaller crack openings in the CW-treated soil. CW inhibits the propagation of cracks and lowers the overall amount of expansive clays, thus preventing excessive volumetric changes. Soltani et al. (2019) and Shahsavani et al. (2020) observed similar wetting and drying behaviour with expansive soils.

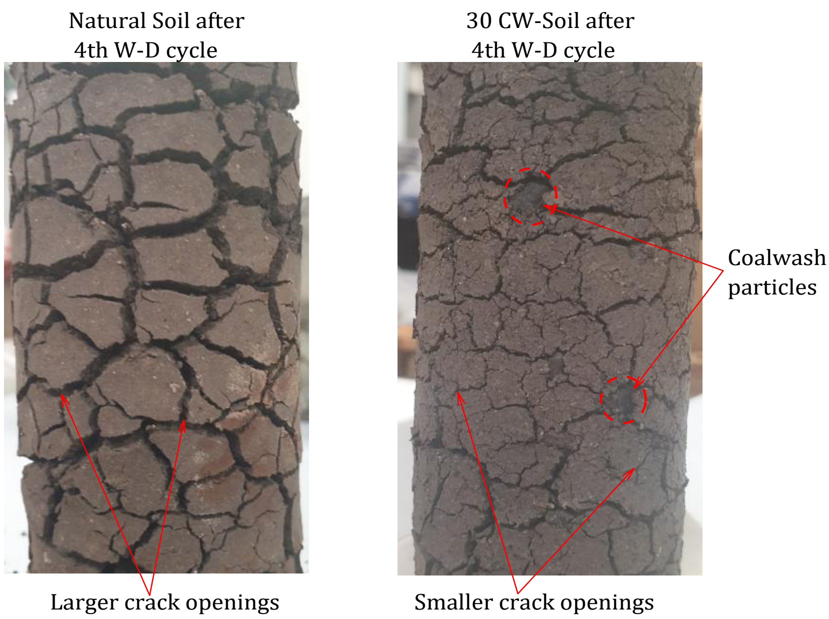

Figure 5. Crack patterns after the 4th wetting and drying cycle on natural and CW treated expansive soil.

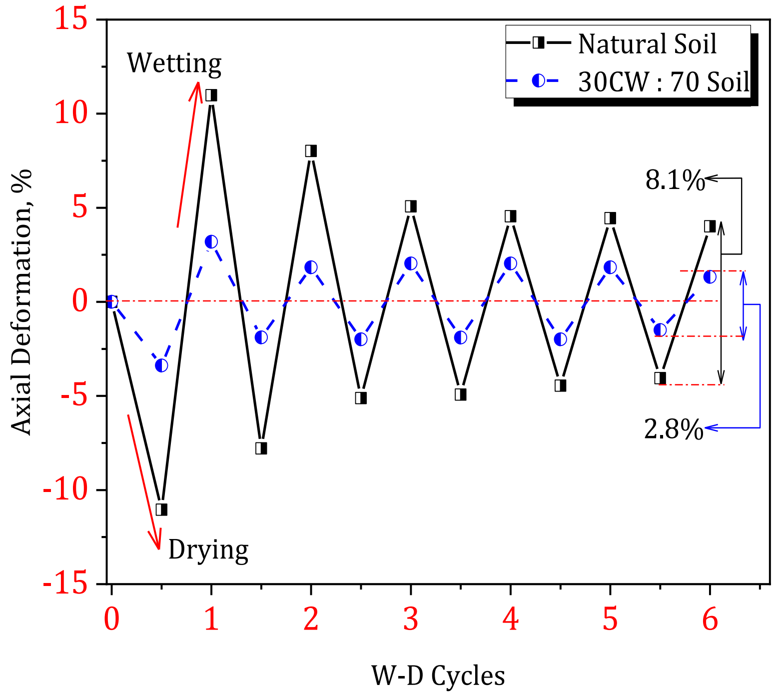

Figure 6. Evolution of axial deformation with wetting and drying cycles.

CONCLUSION

This study assessed the potential of coal wash to alleviate the negative impact of expansive soils through laboratory studies. Atterberg limits, swell pressure, wetting and drying cycles, and unconfined compression tests were carried out on mixtures of CW and soil. The plasticity of the natural soil decreased with the addition of CW, as demonstrated by the 23% and 26% reduction in the liquid limit and plastic limit respectively, with 30% CW. The swelling pressure of natural soil decreased by 36% after the addition of 30% CW by dry weight.

The shear strength of the CW-treated soil was assessed through unconfined compression tests. With 30% CW, the unconfined compressive strength improved by 57% compared to the natural soil. Under an increasing number of wetting and drying cycles, the soil treated with CW experienced higher peak stresses than the natural soils due to the amending mechanisms introduced into the soil by CW particles such as frictional resistance and mechanical interlock. These mechanisms led to a higher strength whilst preventing the propagation of cracks. The axial deformation in natural soil was higher than CW treated soil. The higher the axial deformation, the more the soil structure is destroyed, which results in lower strength under wetting and drying cycles. The observed reductions in volumetric change and increase in strength enable the use of mixed materials in applications such as railway embankments and road pavements.

The objective of the paper is to explore the potential usage of CW to reduce the impact of expansive soil whilst reducing the amount CW that are deposited at landfills annually. However, the chemical and physical characteristics of CW vary from one mine to the other therefore similar study is required on CW sourced from different localities.

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REFERENCES

Alazigha, D. P., Indraratna, B., Vinod, J. S. & Heitor, A. 2018. Mechanisms of stabilization of expansive soil with lignosulfonate admixture. *Transportation Geotechnics,* 14**,** 81-92.

ASTM D698 2000. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)). West Conshohocken, PA 19428-2959: ASTM International.

ASTM D1140-17 2017. Standard Test Methods for Determining the Amount of Material Finer than 75-um (No. 200) Sieve in Soil by Washing. West Conshohocken, PA: ASTM International.

ASTM D4318-05 2005. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA.

Department of Transport and Regional Services. 2007. *Contributing to the Best North South Rail Corridor*. Australia.

Dzaklo, C. K., Rujikiatkamjorn, C., Indraratna, B. & Kelly, R. 2021. Cyclic behaviour of compacted black soil-coal wash matrix. *Engineering Geology***,** 106385.

Estabragh, A., Parsaei, B. & Javadi, A. 2015. Laboratory investigation of the effect of cyclic wetting and drying on the behaviour of an expansive soil. *Soils and foundations,* 55**,** 304-314.

Ferreira, T. M., Teixeira, P. F. & Cardoso, R. 2011. Impact of bituminous subballast on railroad track deformation considering atmospheric actions. *Journal of geotechnical and geoenvironmental engineering,* 137**,** 288-292.

Firoozi, A. A., Olgun, C. G., Firoozi, A. A. & Baghini, M. S. 2017. Fundamentals of soil stabilization. *International Journal of Geo-Engineering,* 8**,** pp. 1-26.

Jung, S. & Santagata, M. 2014. Expansive behavior of coal mine spoils treated with calcium-based stabilizers. *Engineering geology,* 175**,** 46-57.

Kaliboullah, C., Indraratna, B., Rujikiatkamjorn, C. & Heitor, A. 2015. Evaluation of coalwash as a potential structural fill material for port reclamation. *12th Australia New Zealand Conference on Geomechanics (ANZ 2015): "The*

Changing Face of the Earth-Geomechanics & Human Influence". New Zealand: The Conference Company Ltd.

Ma, B., Cai, K., Zeng, X., Li, Z., Hu, Z., Chen, Q., He, C., Chen, B. & Huang, X. 2021. Experimental Study on Physical-Mechanical Properties of Expansive Soil Improved by Multiple Admixtures. *Advances in Civil Engineering,* 2021.

Mckenzie, D. C. 1998. SOILpak for cotton growers. Third ed. Australia: NSW Department of Primary Industries.

Nelson, J. & Miller, D. J. 1997. *Expansive soils: problems and practice in foundation and pavement engineering,* John Wiley & Sons.

Osman, N., Mcmanus, K. J. & Ng, A. Management and analysis of data for damage of light structures on expansive soils in Victoria, Australia. Proceedings of the 1st International Conference on Structural Condition Assessment, Monitoring and Improvement: 12-14 December 2005, Perth, Western Australia, 2005. CI-Premier Pte Ltd.

Seed, H. B., Woodward Jr, R. J. & Lundgren, R. 1962. Prediction of swelling potential for compacted clays. *Journal of the soil mechanics and foundations division,* 88**,** 53-87.

Shahsavani, S., Vakili, A. H. & Mokhberi, M. 2020. The effect of wetting and drying cycles on the swelling-shrinkage behavior of the expansive soils improved by nanosilica and industrial waste. *Bulletin of Engineering Geology and the Environment,* 79**,** 4765-4781.

Soltani, A., Deng, A., Taheri, A., Mirzababaei, M. & Vanapalli, S. K. 2019. Swell–shrink behavior of rubberized expansive clays during alternate wetting and drying. *Minerals,* 9**,** 1-18.

Sridharan, A. & Sivapullaiah, P. V. 2005. Mini compaction test apparatus for fine grained soils. *Geotechnical Testing Journal,* 28**,** 240-246.

Wang, G. & Wei, X. 2015. Modeling swelling–shrinkage behavior of compacted expansive soils during wetting–drying cycles. *Canadian Geotechnical Journal,* 52**,** 783-794.