CASE STUDY: COMPACTION OF COAL ASH FILL BY IMPACT ROLLING AS A METHOD OF SUBGRADE IMPROVEMENT BENEATH A HEAVY DUTY PAVEMENT

R. Rohleder[1], H. Stallard[2]

[1]Associate and Lead Engineering Geologist, [2]Senior Engineering Geologist, Aurecon Australia Pty Ltd, Neutral Bay, Sydney, Australia

ABSTRACT

An intermodal logistics centre for bulk distribution of shipping containers by both road and rail is currently under construction at a site near Enfield in SW Sydney. The 70 ha project site was used as a rail maintenance facility until the early 1990's, when it was largely dismantled. A container terminal yard will occupy approximately one-third of the project site, which will require construction of a heavy duty pavement to support the operational loads. The design of the terminal area is based on construction of a uniform earthworks platform, requiring both cut and fill to attain design levels, to act as a stable subgrade for the pavement layers. Previous studies revealed the presence of poorly compacted fills across the site that vary significantly both in composition and thickness. Of particular interest was the presence of a significant volume of coal ash fill, which was the thickest fill deposit across a large part of the site. The coal ash was found to be poorly compacted, but laboratory testing indicated it could achieve high strength and CBR index values when compacted to a dense state. The coal ash could thus be treated in place and incorporated into the subgrade earthworks or it could be mined and re-used as general fill in other parts of the site. A programme of field compaction trials was implemented, using conventional vibratory rollers and also impact rollers to determine the optimum compaction method for the coal ash and other fill materials. The field trials showed that compaction of the coal ash significantly reduced its void ratio by approximately 30% with corresponding settlement on compaction. The outcome of these field trials enabled the contractor to develop a ground treatment methodology tailored to the fill material type, which also conformed to the design specification for the subgrade layers.

1 INTRODUCTION

Coal combustion products, or 'CCPs', is the collective name for a range of by-products derived from the combustion of various grades of coal, primarily in the power generation industry. These materials have been generated throughout the developed world over the last 50 years and a multi-billion dollar secondary industry has arisen from the commercial re-use of these products. In the United States in particular, it is estimated that 131 million tons of CCPs were generated in 2007, of which about 43% was used beneficially with the balance being disposed of in landfills (ACAA, 2012). Driven by environmental concerns, including the environmental costs associated with mining source materials, there is growing pressure to increase the beneficial utilisation of CCP products.

In Australia, production of CCPs is generally limited to coal-fired power stations. By-products such as flyash and bottom furnace ash are commonly recycled, processed and supplied commercially by the aggregates industry. These conventional coal combustion by-products have been extensively researched and their properties have been assessed and categorised as part of the industry's product certifications. However, although not economically significant in comparison to the volumes generated by the power generation industry, an unknown number of historical CCP landfill deposits exist that are associated with other industries in Australia. The focus of this case study is one such occurrence. The fill deposit described here is a coal ash material derived from the cleaning of railway steam engines at a maintenance and marshalling facility previously known as the Enfield Marshalling Yards, in Sydney's inner west. The facility operated from the 1920's through to the early 1990's when it was largely dismantled. Preliminary ground investigations conducted at the site revealed the presence of a discrete deposit of coal ash fill in the central northern part of the site with an estimated volume of 100,000 m^3.

A case study is presented in this paper that describes the process followed to characterise the coal ash material and assess its suitability for re-use as an earthworks construction material in the proposed development of the site as an intermodal container terminal.

2 SITE DESCRIPTION

2.1 SITE LOCATION AND GEOLOGY

The project site is roughly 2300 m in length and 320 m wide and occupies an area of approximately 70 ha. The existing Enfield sidings border the length of the site on the west side. Ground levels vary from about 31 m AHD at the north end to about 17 m AHD in the south end adjacent to a canal and culvert drain (Cox's Creek). A site location map is shown in Figure 1 below.

Figure 1: Project site location.

The project site is underlain by the Ashfield Shale formation of the Wianamatta Group, and is characterised by shaly mudstones, laminates and subordinate siltstone in thin layers. Prior to the development of the railway yards, the original landform probably consisted of low-lying ridges and shallow streams with low relief. The shale bedrock surface was probably not exposed, but lay beneath a relatively thin cover of residual or alluvial fine soils, typically clayey. The area may have been swampy in parts, particularly close to the former streams. Extensive cutting and filling during the early construction of the railway yards resulted in expansive areas filled with the excavation spoil, commonly not more than 1 m to 2 m thick.

2.2 FILL TYPES AND DISTRIBUTION

The project site has been the subject of several ground investigations during the last 10 years, following the closure of the railway maintenance facility. Over 150 trial pits and about 50 boreholes have been logged across the site, which provide the geotechnical database for modelling the ground profile. Light dynamic cone penetrometer tests (DCP's) were usually undertaken adjacent to test pit locations to record the soil consistency over the top 2 m or so.

Interpretation of the various logs and associated soil classification laboratory test data indicated that the various fill materials encountered across the project site could be broadly divided into 6 types. Of these, 3 types were considered to occur widely, the other types occurring in isolated pockets or minor amounts. The three predominant fill types are:

Table 1: Predominant fill types encountered.

Fill Type Symbol	Material Description	Thickness and Occurrence
Fca	Coal Ash (with minor flyash)	Up to 5.6 m thick. Occurrence generally limited to the central northern half of the project site. Covered by thin (~ 0.5 m) layer of ballast or other fill
Fgc	Well graded gravelly Clay and clayey Gravel	Both these types occur widely and commonly at the same location in the vertical fill profile. Generally < 2 m thick across the south half of the project site. Thick deposits, up to 9 m thick, were found to occur adjacent to the main coal ash deposit to the west of the site
Fcl	Predominantly Clay with minor amount of gravel and sand	

The subordinate fill types consist of railway ballast (mixed with some clay and coal ash), cobble and boulder sized rock fragments in a gravelly clay matrix and undifferentiated gravelly clay with abundant industrial rubble including bricks, timber, concrete, steel and plastics. Generally, little or no organic or putrescible rubble was found across the site.

The fill type, Fgc, was interpreted to represent the excavation spoil from 1920's earthworks and is thus a reworked material consisting of shale fragments in a clayey matrix. A site plan showing fill thickness zones (<2 m, 2 m-4 m and >4 m in thickness) was prepared and it became evident that the project site could be divided into a southern half where the fill cover was generally thin (typically around 1 m thick) over weathered shale bedrock and the northern half where the thickness of fill was much greater included a large zone of coal ash. A simplified plan showing the fill thickness distribution across the northern half of the site is shown in Figure 2 below. The plan includes the trace of a coal ash stockpile known to have existed at the site that is visible in a 1943 historical aerial photograph sourced from NSW government Survey department.

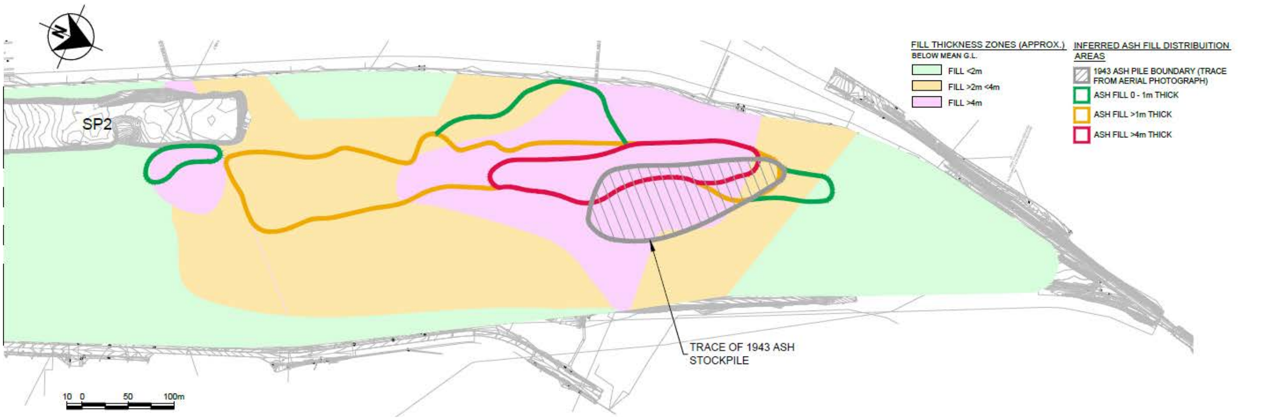

Figure 2: Distribution of Fill and Coal Ash thickness across north half of Enfield ILC site.

The plan confirms that the bulk of the coal ash deposit lies within an elongate area approximately 350 m in length by 50 m wide (area with red perimeter in Figure 2). It is postulated that coal ash stockpiles that built up over the years were buried in adjacent deep excavations with residual material spread out in nearby areas before capping with a thin layer of gravelly clay (excavation spoil) fill.

3 COAL ASH DESCRIPTION

3.1 GENERAL DESCRIPTION

The coal ash material is a dark grey to black, well-graded, sand to gravel size material comprised of a composite mixture of angular to globular shaped ash, clinker and coal fragments (collectively termed coal ash). In places, the coal ash contains thin, discontinuous layers or pockets of a whitish, more uniformly graded, sand-sized flyash material. The flyash material represents the more volatile combustion by-product recovered from the steam engine chimney flues. Within the coal ash deposit, the proportion of light coloured flyash to black/grey coal ash was estimated to be generally less than 10% by volume.

The coal ash was described as being a non-plastic, porous, nearly dry material displaying a loose consistency. A weak cementation was noted in places where the material forms cobble-sized lumps. This was more common in the flyash material and is attributed to a weak pozzolanic cementation. Penetrometer field test results in the coal ash are also indicative of a loose to medium dense consistency with typical SPT N_{300} values in the range 2 to 5, and DCP N_{100} values showing more variability with a typical range between 1 and 7 blows.

3.2 MATERIAL PROPERTIES

3.2.1 Laboratory testing

Bulk samples of coal ash material were recovered from a number of trial pits during recent ground investigations. Laboratory tests were undertaken on these samples to determine its compaction characteristics. The results of these tests with typical range of values are given in Table 2 below.

Table 2: Coal Ash – laboratory compaction characteristics.

Property	Value (range; mean in brackets)
Particle density (in Mg/m^3)	2.13-2.19 [2.17]
Std. Max. Dry Density (in Mg/m^3)	0.95-1.19 [1.05]
Optimum moisture content (%)	15.0-39.3 [24.3]
Void ratio, e, at mean SMDD	1.07
CBR (4-day soaked) at 95% SMDD	19-50% [30%]

The low dry density values obtained are within the range of values typically obtained from CCPs, although the particle density (and consequently, void ratio) are in the lower range of values. This may be attributed to the presence of closed micro-bubbles trapped within the coarser fragments (typically of clinker) (Trivedi and Sud, 2004). As the test method for particle density (AS1289 3.5.1) screens out particles larger than 2.36 mm, followed by crushing, it is likely that the specific gravity representative of the mass of coal ash particles is even lower than the values shown in Table 2. Indeed, many of the coarser particles recovered during trial pit logging were found to initially float on water. The range of optimum moisture contents obtained suggests the material is not too sensitive to moisture to attain peak density, which is also a characteristic of purely granular materials.

The high values of optimum moisture content obtained, compared to natural granular soils, are attributed to a combination of low particle density and the relatively high porosity (approximately 48%) when compacted. It is postulated that some interstitial water is trapped by suction forces in open pores, thus accounting for the high moisture content levels even though the material behaves as a free-draining material.

Figure 3 below shows particle size grading curves for coal ash material, including two samples of flyash. The curves generally confirm the material is well graded and mainly sand and gravel size. The flyash material, however, differs in that the size is more uniform (poorly graded) and in the medium sand range (hence sugary texture).

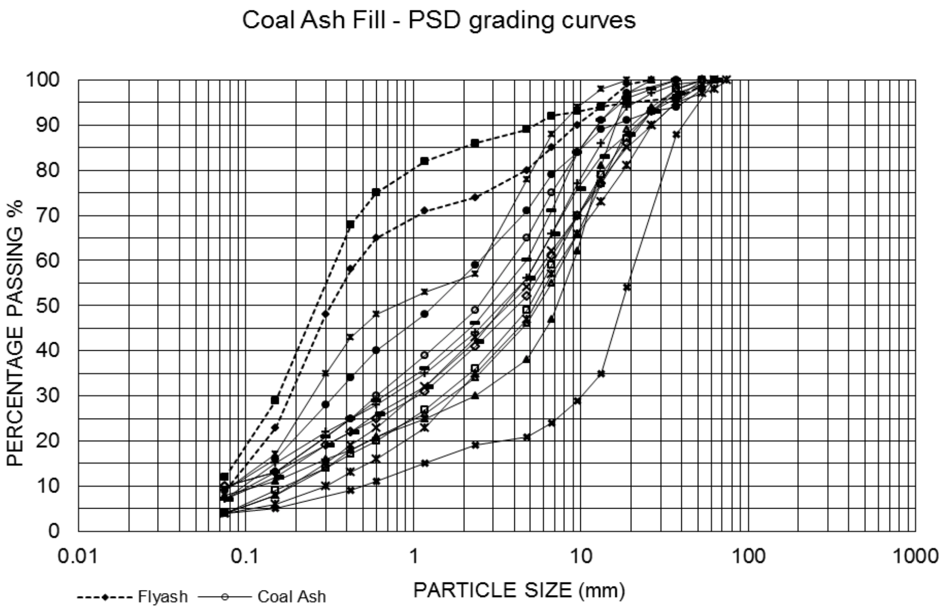

Figure 3: Particle size distribution of coal ash fill at Enfield site.

3.2.2 *In situ* Density

During an early works stage of construction, a programme of field compaction trials was planned with the aim of assessing the optimum field compaction method for the coal ash material (and other fill types). Two trial pad areas were selected on the coal ash, each 75 m in length and 10 m wide. The ground profile at each of these trial pad locations indicated a coal ash thickness significantly greater than 4 m, below a thin capping less than 0.5 m thick.

As part of the control testing carried prior to compaction trials, the capping was removed from each of the trial pad areas (top 300 mm or so was stripped) and the surface of the coal ash exposed so that the field density could be obtained using a nuclear density gauge. Samples were also obtained (6 locations per trial area) so as to verify the moisture content and also to undertake Hilf rapid compaction tests (method AS1289 5.7.1).

The results of the field density determination within the two trial areas showed that the *in situ* dry density is variable over the upper surface of the coal ash deposit, with values ranging from 0.90 Mg/m^3 to 1.50 Mg/m^3. The higher values tend to occur where the coal ash has been mixed with some of the capping material. The Hilf density ratio was found to vary between 70% and 100% across the surface. The higher values were attributed to parts of the trial pad that may have been subjected to construction traffic or plant movements in the past (during previous demolition works).

Below this upper, stiffer layer the coal ash is mostly loose to medium dense and field density readings obtained after the compaction trials recorded dry density values mostly ranging from 0.70 Mg/m^3 to 0.90 Mg/m^3. Adopting a mean value of 0.80 Mg/m^3 for untreated coal ash, it can be calculated that a reduction in void ratio from 1.71 to 1.18 would result if a target compaction of 95% of SMDD could be achieved in the field. This reduction in the void ratio corresponds to a reduction of about 30% per unit volume of coal ash material.

3.2.3 Collapse Potential

As the loose coal ash material is essentially a granular material with a relatively high void ratio, there was a concern that the material could exhibit collapse settlement behaviour in response to flooding or saturation. The coal ash was found to be mostly free-draining, and any surface water rapidly infiltrated through the material, with some seepage noted in trial pits at the base of the coal ash where it overlay a less permeable clay layer (such as residual clay). The groundwater table in the areas containing coal ash was found to lie below the base of the deposit at all locations.

In order to assess the collapse potential of the coal ash 4 sets of double oedometer tests were conducted in the laboratory on remoulded samples obtained from the two trial compaction areas. The test procedure generally followed the method prescribed by ASTM D5333, except that the applied stress at inundation was maintained for a maximum of 2 hrs rather than the recommended 24 hr on account of the small change in strain measured following inundation. The sample properties set for the tests are tabulated below.

Table 3: Sample properties in collapse potential tests.

Sample Source	Specimen compaction	Initial void ratio (e_0)	Stress (kPa) at inundation	Δe at inundation
CT-1	0.80 Mg/m^3 at 10% m/c (~76% SMDD)	1.513	100	0.006
(2.7-3.0 m)	1.00 Mg/m^3 at 35% m/c (~95% SMDD)	0.977	100	0
CT-2	0.80 Mg/m^3 at 10% m/c (~76% SMDD)	1.513	100	0.002
(3 m)	1.00 Mg/m^3 at 35% m/c (~95% SMDD)	1.000	100	0.002

As indicated, all four samples were inundated at 100 kPa applied stress following which an additional increment up to 200 kPa was applied prior to unloading. Parallel control tests were run without any inundation for each sample in accordance with the test procedure. The exception to this was the dense sample from CT-2, for which there was insufficient material left to conduct the control test without inundation. The consolidation curves obtained for all the tests are presented below.

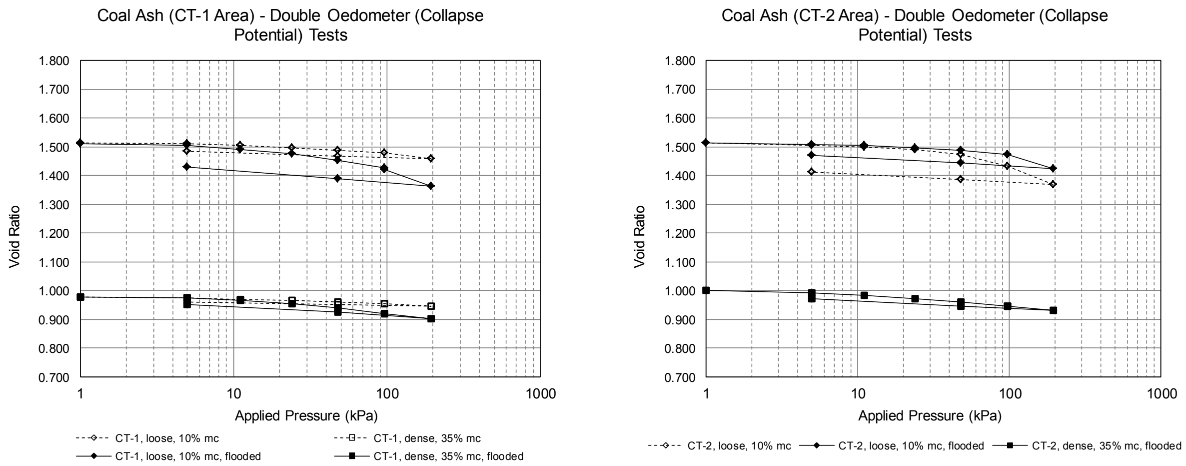

Figure 4: Settlement performance of IR compaction trial areas.

The collapse potential (I_c) is defined in ASTM D5333 in terms of void ratio and may be calculated based on any appropriate stress level at inundation. For this project, a stress of 100 kPa was considered appropriate for a pavement design loading of 70 kPa. In addition, ASTMD D5333 defines a collapse index (I_e) as the value of I_c under an applied stress of 200 kPa at inundation. A value of I_e less than 0.002 is considered to represent a slight to negligible collapse on inundation.

Trivedi and Sud (2004) carried out detailed studies on the collapse behaviour of various types of coal ash material from Indian power stations. These included flyash, coal ash and bottom furnace ash. Figure 5 below shows average collapse potential values obtained by the authors on different samples (at 80% relative compaction). Plotted on this graph are the collapse potential values obtained from the four inundated samples from the Enfield project site. The graph shows that the values of I_c from the two loose samples (~76% relative compaction) are roughly comparable to the lowest values obtained by Trivedi and Sud. It is generally accepted that a collapse potential (I_c) result below 0.01 implies negligible risk of collapse settlement occurring in the field.

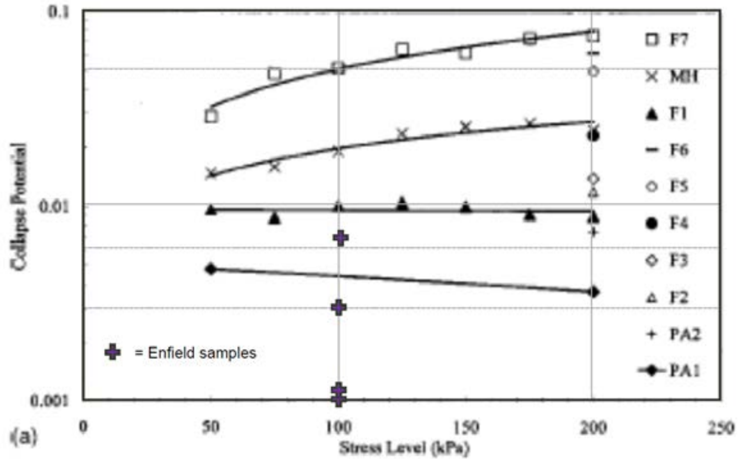

Figure 5: Collapse potential (I_c) values for Enfield samples compared to Indian coal ashes.

These tests, and comparison of the results obtained with other studies on coal ash material, strongly suggest that collapse settlement behaviour is unlikely to occur within the coal ash deposit at either existing or post-compaction densities under the proposed design loads.

4 FIELD COMPACTION TRIALS

Preliminary design of ground treatment options targeted the *in situ* compaction of the thick fill areas by conventional methods, including vibratory roller compaction, impact roller compaction and also dynamic compaction methods. Allied to this, settlement analysis of the ground model for pavement design indicated that a target thickness of treated and/or engineered new fill equivalent to not less than 67% of the total fill thickness, where the existing fill thickness was greater than 2 m, should be realised. This would result in a stiff subgrade beneath the structural pavement such that predicted settlement (and in particular, differential settlement) would not exceed the pavement deflection limit of 1:200 beneath a 70 kPa design pressure at top of subgrade.

In order to limit the amount of excavation and replacement of untreated fills in these areas, the earthworks contractor sought to maximise the depth of existing fill that could be improved *in situ*. A process of evaluating the costs associated with the proposed treatment methods was followed that eventually led to impact rolling being selected as the most cost-effective method for improving the coal ash fill deposit.

4.1 IMPACT ROLLING

The two compaction trial pad areas were subjected to compaction by impact rolling using a tractor-towed Landpac 17.5t, 3-sided, impact roller imparting a kinetic energy of 135 kJ per blow. The field trials comprised compaction in increments of 6 or 12 passes of the roller until the average increase in settlement fell to an approximately constant value. Compaction control tests were undertaken after each set of passes, which included DCP tests near the 4 corners and field density readings (using nuclear density gauge) at 6 locations. A photo of the impact roller employed for the trials is shown below.

Photo 1: Landpac 17.5t 3-sided impact roller used in field compaction trials.

4.2 ROLLER COMPACTION CONTROL SYSTEMS

Two real-time, computerised methods were employed to track the compaction process and monitor its effectiveness. One method was by means of an integrated compaction control system on board the Landpac impact roller. The system relies on a differential GPS to track the route of the roller on a coordinated plan. The key components of the system are the Compaction Impact Response (CIR) system that records the deceleration of the drum axle (range being from 0 to 9xg) and a Continuous Impact Settlement system that records the average cumulative settlement after each set of passes. A "High" to "Very High" CIR response is obtained with decelerations greater than 6xg, which correlate to a rigid ground response (and thus relative high surface stiffness).

The second method employed in these trials made use of a 13t Amman instrumented, vibratory, smooth roller fitted with the Amman proprietary 'ACE' compaction control system. This roller effectively performed a proof roll once the compaction by the impact roller was completed. Between 3 and 4 single passes were needed to cover the trial pad area. By means of the on-board ACE system, the deceleration of the drum axle is converted to a stiffness coefficient termed the roller-determined soil stiffness (kB in units of MN/m). The ACE software relies on a series of algorithms that relate the inertial forces generated by the roller drum to the soil behaviour modelled as a spring-viscous dashpot model (Mooney and Adam, 2007).

5 RESULTS OF FIELD TRIALS

The two compaction trial pad areas were designated as areas CT-1 and CT-2. A summary of the compaction process followed in each area is tabled below.

Table 4: Compaction process in trial areas CT-1 and CT-2.

Trial Pad	Coal Ash thickness	Cumulative number of Impact Roller (IR) passes	Comments
CT-1	6.4 m	6 ,12,24,36,48,60 + Amman 13t Proof Roll	The surface of each pad was flooded with approx. 20 kL of water, left overnight before the next set of passes
CT-2	6.2 m	12,24,36,48,60,72,84 + Amman 13t Proof Roll	

Each trial pad surface was inundated with water after 36 passes with the aim of saturating the upper zone of coal ash. This was carried out to check if a collapse settlement response could be induced in the relatively uncompacted zone of coal ash directly beneath the compacted upper crust.

The coal ash thickness was found to be relatively uniform across both pads, except beneath one end of pad CT-1 where the coal ash thickness reduced to about 5.0 m with a somewhat stiffer crust in the upper 0.5 m.

5.1 ROLLER COMPACTION CONTROL OUTPUTS

5.1.1 Settlement Performance

The settlement performance of the surface of each trial pad area, in terms of average incremental and cumulative settlement across each lot is shown in Figure 6 below (output of IR CIS system).

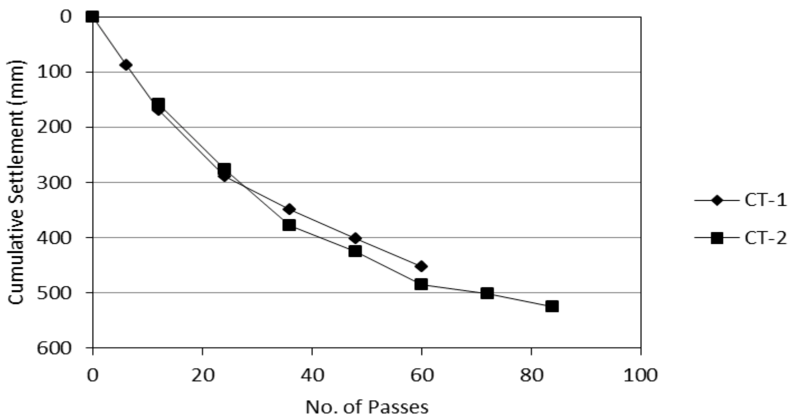

Figure 6: Settlement performance of IR compaction trial areas.

The results indicate that the coal ash material showed similar settlement behaviour in both trial areas. Although the number of passes in CT-2 was extended to 84 passes, the total settlement in each area after 60 passes was 452 mm and 485 mm, respectively. There was no obvious collapse settlement response noted following saturation of the trial pad areas after 36 passes of the roller.

5.1.2 Measurement of Stiffness Response

Figure 7 below shows the combined outputs from the IR CIR soil response system and the values of the roller-determined stiffness (kB) obtained following final passes with the Amman instrumented roller.

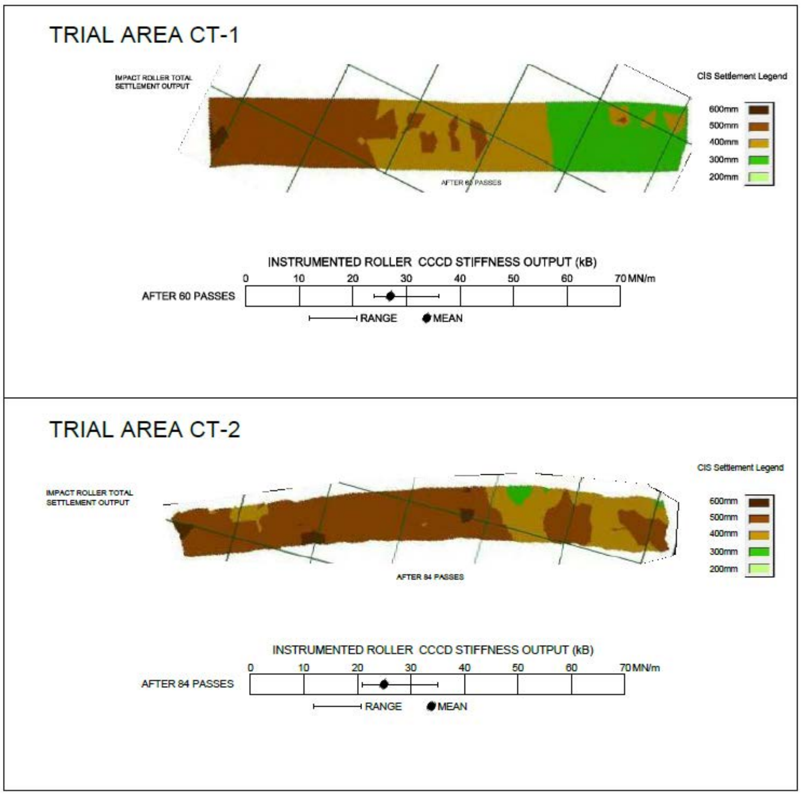

Figure 7: Soil behaviour (stiffness) response in IR compaction trial areas.

The results show that a "stiff" response, as measured by the IR CIS system, was obtained across most of each area after 60 passes in CT-1 and 84 passes in CT-2. The extra number of passes required to achieve this condition in CT-2 is attributed to more variability in the pre-compaction near surface stiffness of the coal ash at this location.

The stiffness values obtained from the Amman roller showed similar range of values in the two trial areas. The average values recorded were 27 MN/m and 25 MN/m in areas CT-1 and CT-2, respectively. As the output along each track is a continuous linear plot (against tracked distance), lower value 'spikes' are indicative of soft spots, thereby testifying to the capacity of the instrumented roller to perform a proof-roll simultaneously.

5.2 DENSITY

5.2.1 Field Density Measurements

The field density of the coal ash material was measured with a nuclear density gauge at 6 locations, and repeated at the same location after each set of passes. At the completion of the compaction trials, it was decided to excavate two large rectangular pits transversely across the middle section of each trial pad. This served a number of purposes, including detailed logging of the coal ash deposit with depth (each pit was excavated to the base of the coal ash), DCP profiling at regular depth intervals to obtain a full depth DCP N_{100} blowcount profile, and measurement of field density at 0.5m depth intervals. In addition, by extending the excavation a few metres beyond the treated area, DCP and field density profiling was duplicated through the untreated zone for comparison with the results obtained beneath the compacted area.

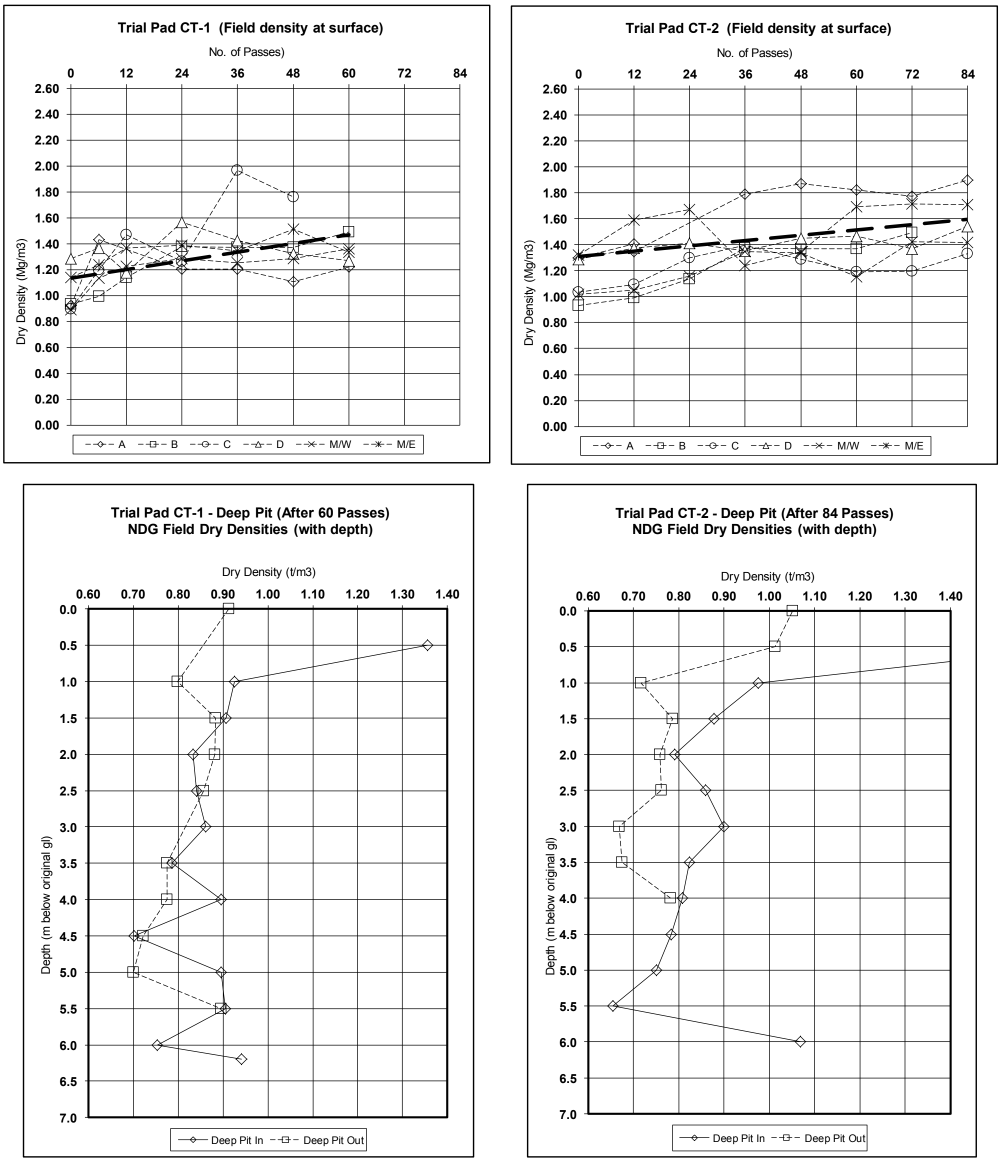

Figure 8: Field density profiles in IR compaction trial areas.

The results show that the dry density of the near-surface layer (~0.3 m or so) of the coal ash in the two trial areas was about 1.20 Mg/m^3. However, the corresponding mean Hilf density ratio is about 84%, which suggests that the coal ash was not pure but may have been mixed with some capping material (e.g. ballast). In both trial areas there is a consistent increase in the dry density of the material at the surface with repeated passes of the impact roller. The trendlines (shown on the two upper graphs in Figure 8) indicate a percentage increase in dry density of about 25% in CT-1 and 15% in CT-2 after 60 passes.

The depth of influence of the impact roller is indicated by comparison of the dry density profiles with depth obtained from a location within the treated area and a location a few metres beyond the edge of the treatment area. It can be seen from the two lower graphs in Figure 8 that the zone of densification extends to approximately 1.0m below the original surface level (prior to compaction), for a dense state corresponding to a dry density of about 1.0 Mg/m^3 (or 95% SMDD). These results imply that impact rolling, after 60 passes, results in densification of the upper 1.0 m of the coal ash deposit with a consequent surface settlement of about 0.5 m. Improvement does appear to extend to about 1.5 m below original ground level although the lower 0.5 m does not quite achieve the same level of compaction.

5.2.2 DCP Profiling

The consistency of the coal ash material over its full depth was also assessed by means of DCP tests undertaken within the treatment area and a few metres beyond the edge in the two trial areas. Figure 9 shows plots of the N_{100} values obtained following completion of the compaction process. The plots are seen to be generally consistent with the field density profiles and also indicate that the improvement from impact rolling has extended to a depth of approximately 1.5 m below original ground level (allowing for 0.5 m settlement of the treated surface).

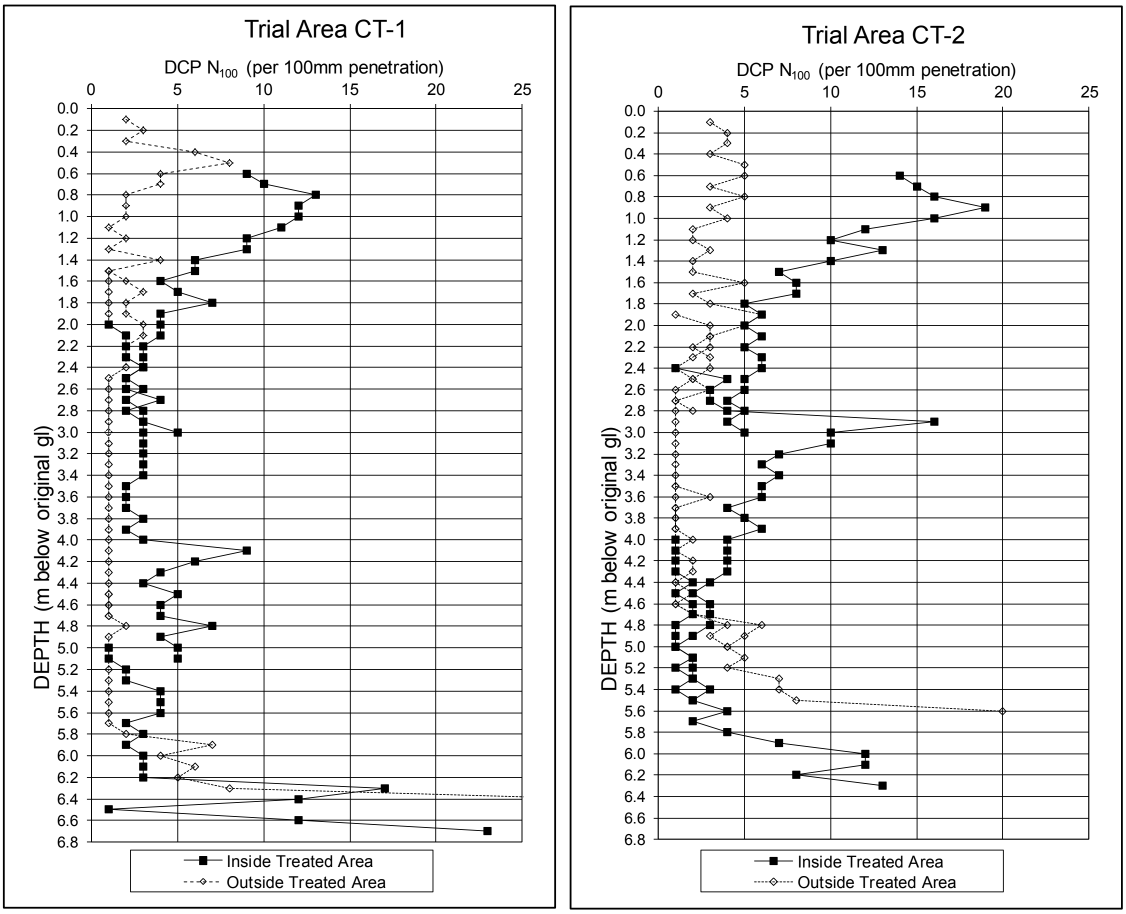

Figure 9: DCP profiles in IR compaction trial areas.

The above observations, in respect of field density and DCP blowcount profiles, are deemed to be consistent with the predicted reduction in volume of about 30% derived from a decrease in void ratio from the loose state to that in a dense state (at 95% of SMDD) for the coal ash material within the depth of influence of the impact roller.

The mean DCP N_{100} value within the improved zone is about 8 with a lower-bound value of about 5. A correlation between SPT N_{300} and DCP N_{100} such that STP N_{300} = 1.5 x DCP N_{100} (based on comparison of kinetic energy levels) was adopted. Therefore, a corresponding lower-bound value of SPT N_{300} equal to 8 was considered indicative of coal ash material that has been compacted to minimum 95% of SMDD.

5.3 ESTIMATION OF DEFORMATION MODULUS

There are not many methods available to obtain a reliable measure of the modulus of deformation (E_m) in granular soils. Most derivations of modulus are based on empirical correlations with field tests such as SPT N value, CPT cone resistance, or plate load tests. Laboratory oedometer tests are useful to obtain a measure of the constrained modulus (vertical strain only) that approximates one-dimensional consolidation beneath large loaded areas. It should be pointed out that laboratory oedometer tests on recompacted samples of granular materials are not always reliable due to scale and sampling factors.

No *in situ* load tests were carried out on the coal ash material for this project and reliance on estimation of the constrained modulus was based on the 4 sets of double oedometer tests and empirical correlation with SPT N value (after Stroud, 1988) for non-cohesive materials. From the oedometer tests, the compression secant modulus calculated for the stress range from 5 kPa (seating load) to 100 kPa was obtained based on the approximation $E \sim 1/m_v$ for one-dimensional consolidation. This stress range covers the likely range of applied stresses that will be experienced by the subgrade materials under the design working pressures. The correlation with SPT N was based on the approximation $E = N_{300}$ for loose coal ash and $E = 2N_{300}$ for coal ash treated in place by impact rolling. The corresponding modulus values obtained from these methods are shown in the table below.

Table 5: Adopted values of modulus of deformation (E_m) for coal ash

Relative Density	E_m (MN/m^2)	Correlation with
Loose (<75% SMDD)	3	Typical SPT N_{300} = 2 recorded in a number of boreholes; Two oedometer tests produced mean value of 5.2 MN/m^2
Dense (min. 95% SMDD)	16	Minimum SPT N_{300} = 8; Single oedometer test produced value of 8.6 MN/m^2

The value of 16 MN/m^2 derived for coal ash compacted to minimum 95% SMDD is comparable to the range of values obtained by Kim and Prezzi (2007) for Class-F flyash recovered from three different coal-fired power stations in the state of Indiana, USA. Their studies showed a range of tangential constrained modulus ranging from about 5 MN/m^2 to about 20 MN/m^2 for a stress range between 0 and 200 kPa.

The modulus values obtained for densely compacted coal ash are relatively low when compared to typical sands and gravels compacted to a similar degree of compaction. Although the CBR index values are high (>20%), it is postulated that some of the coarser particles (containing micro-bubbles) may be susceptible to crushing under a threshold contact pressure even though the individual particle strength is high. In this regard Trivedi and Sud (2004) reported that the specific gravity of coal ashes increased as the fineness of the ash increased due to the release of entrapped gases. This phenomenon could account for the relatively low increase in modulus values with increasing density and applied stress.

6 CONCLUSIONS

A coal ash landfill deposit, originating from the cleaning of locomotive steam engines, was the focus of an investigation to determine the efficiency of impact rolling as a means of field compaction of the material *in situ*. The properties of the coal ash were assessed by various laboratory tests and by field compaction trials in two control areas. The field trials provided information on the *in situ* properties of the material both before and after compaction. In general, the following conclusions were drawn from the results of the study:

(i) The coal ash deposit was found to be typical of CCP's in general, with a low maximum dry density (standard) of about 1.05 Mg/m^3 and a specific gravity of 2.17. The void ratio at SMDD is approximately 1.07. The soaked CBR (at 95% of SMDD) ranges from 19% to 50% in the samples tested with a mean value of 30%.

(ii) The *in situ* density of the coal ash deposit in the two trial areas was found to range between 0.70 and 0.90 Mg/m^3 beneath a thin surface capping with a corresponding average void ratio of about 1.71, this representing a loose to medium dense consistency. Densification from the *in situ* state to a dense state corresponding to 95% of SMDD was expected to result in a reduction in volume of about 30% over the treated depth.

(iii) Collapse potential of the coal ash at its *in situ* density was investigated by means of two sets of double oedometer tests with saturation at a 100 kPa stress level. The tests produced a collapse potential (I_c) of less than 0.01 suggesting that the potential for collapse settlement on inundation at this applied stress level would be negligible.

(iv) Field compaction trials using a 17.5t, 3-sided impact roller showed that the coal ash material responded very well to this method of field compaction. In general, about 60 passes were required to improve the top 1 m to 1.5 m with a consequent loss of ground (due to compaction settlement) of just under 0.5 m. The improvement was confirmed by field density profiling and dynamic penetrometer (DCP) profiling over the full thickness of the deposit in deep pits excavated across both treated and untreated zones.

(v) The DCP was found to be a practical tool for obtaining a quantitative assessment of the depth of the treated zone. By correlation, a minimum DCP N_{100} blowcount value of 5 corresponds to an SPT N_{300} value of 8, and this was found to be the minimum value corresponding to an achieved minimum density of 1.00 Mg/m^3 (equivalent to 95% of SMDD).

(vi) Although the shear strength of the compacted coal ash appears to be relatively high, as indicated by the CBR index values, the stiffness of the material is not appreciably increased on compaction. Despite not having undertaken any field plate load tests, it was estimated from the oedeometer test data and empirical correlations with penetrometer values that the constrained modulus (E_m) of the coal ash increased to about 16 MN/m^2 when compacted to 95% of SMDD, from a low value of about 3 MN/m^2 in the loose state. This is in line with similar range of values obtained in other studies with coal ash products. Further tests involving particle size analyses after compaction under varying stress levels would be needed to establish if particle crushing under a threshold contact pressure is a factor that could explain this.

7 REFERENCES

American Coal Ash Association (ACAA) Educational Foundation, 15200 E. Girard Ave., Ste. 3050, Aurora, CO 80014-3955, USA.

ASTM D5333-03. Standard Test Method for Measurement of Collapse Potential of Soils. ASTM International, P O Box C700, West Conshohocken, PA 19428-2959, USA.

Kim, B. and Prezzi, M. (2008): *Evaluation of the mechanical properties of class-F fly ash*. Waste Management, Vol 28, p649-659. Elsevier Ltd.

Mooney, M. and Adam, D.: *Vibratory Roller Integrated Measurement of Earthwork Compaction: An Overview.* ASCE Seventh International Symposium on Field Measurements in Geomechanics, 2007.

Trivedi, A. and Sud, V.K.: *Collapse Behaviour of Coal Ash.* Journal of Geotechnical and Geoenvironmental Engineering, ASCE, April 2004, p. 403-415.