REPORT ON POTENTIAL FOR BACKFILLING BORD AND PILLAR VOIDS USING FLY ASH SLURRY

TO

CSIRO

BY

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EXECUTIVE SUMMARY

In various locations worldwide, fly ash slurry has been injected into underground bord and pillar coal mine workings to provide support, and the method has recently been used successfully for the Ipswich Motorway upgrade. It is also being considered to provide support to historical bord and pillar workings beneath the suburb of Collingwood Park. The purpose of the laboratory testing described in this report is to provide guidance for the application of fly ash slurry injection at Collingwood Park.

The testing carried out on fly ash from Swanbank Power Station comprised (i) laboratory characterisation testing of the fly ash at The University of Queensland (UQ), (ii) flume testing of slurried fly ash at UQ, and (iii) field testing, profiling, and sampling and testing at UQ, of an old fly ash beach at Swanbank Power Station.

According to the particle size distribution data, Swanbank fly ash classifies as a Gravelly, Clayey, Sandy SILT, while according to the Atterberg Limit data it classifies as a CL (Gravelly, Sandy, Silty CLAY of low plasticity), although the former is a better description. The specific gravity of the Swanbank fly ash solids averages 2.09, substantially less than that of normal mineral matter (being 2.65 to 2.7). Swanbank fly ash has an alkaline pH averaging 9.09 and a moderate Electrical Conductivity averaging 351 µS/cm.

On settling, the final % solids of Swanbank flay ash increases with decreasing initial % solids (64.9% solids from 55% solids initially to 72.2% solids from 35% solids initially), as does the dry density, while the final total moisture content decreases with decreasing initial % solids. The initial and final wet densities (which drive settling) vary least with initial % solids. At an initial % solids of 50% (i.e. in a slurry state), Swanbank fly ash has low undrained and drained strength parameters, which would increase with drainage and consolidate to a more "soil-like" consistency. A very low Compression Index C_c of 0.0455 is calculated for Swanbank fly ash placed initially at 50% solids, together with a very high Coefficient of Consolidation c_v and a high Coefficient of Volume Decrease m_v, and the calculated Hydraulic Conductivity k is relatively low (in the range from 10^{-8} to 10^{-9} m/s).

Unflooded, unconstricted laboratory flume beaching tests on Swanbank fly ash produces the steepest beach (averaging about 1%) for an initial % solids of 55%, lower but insensitive beach slopes over the intermediate range of initial % solids, and a flat beach for an initial % solids of 15%. The average field beach slope of 0.014% is similar to that obtained in the laboratory for an initial % solids of 15% (similar to the field initial % solids), and the non-dimensional beach profile is similar to that for the field profile. Unflooded, constricted laboratory flume beaching tests produces a significantly steeper beach at high initial % solids, and only a slightly steeper beach at intermediate initial % solids. Flooding generally has little effect on the average beach slope for unconstricted beaching.

Constricted backfilling laboratory flume tests under water and a head of slurry highlight the dramatic effect of applying a head of slurry in increasing the final % solids and dry density (from about 1.0 g/cm^3 without an applied head to about 1.5 g/cm^3 with an applied head), and driving the filling (through fluidisation) of the constriction following initial settling within it. Applying a high head of slurry appears more effective in driving backfilling than applying a higher initial % solids.

To facilitate the backfilling and support of bord and pillar roadways and openings with fly ash slurry to provide some support, the following guidelines are suggested:

1. Voids should first be blocked off downslope of the delivery point for the fly ash slurry, to contain the slurry.

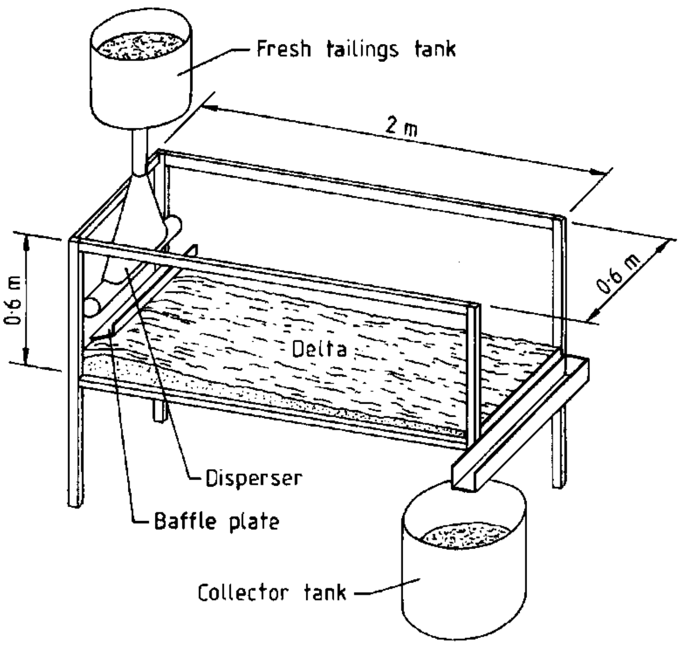
2. The optimum initial % solids for the fly ash slurry appears to be in the range from 50 to 60%, to limit the average beach slope and hence maximise initial filling, to make the slurry more capable of fluidising to facilitate void filling following settling, and to increase the final dry density, strength and stiffness achieved. The actual optimal initial % solids will increase with the applied head of fly ash.
3. A head of slurry should be applied in the borehole used to deliver the fly ash slurry, which will facilitate void filling and gain in dry density, strength and stiffness.

1 INTRODUCTION

This report presents the results of a limited literature review and laboratory testing to investigate the potential for backfilling bord and pillar voids formed on historical underground coal mining in the Ipswich Coalfields using fly ash slurry from Swanbank Power Station. The investigation was carried out at The University of Queensland (UQ) Geomechanics Laboratory under the supervision of Professor David Williams, with the detailed testing carried out by fourth year thesis students Mokshadsing Ramlackhan and Daniel Spriggs. Supervision input was also provided by Drs Baotang Shen, Habib Alehossein and Johnny Qin of CSIRO.

The proposed testing was outlined in proposals dated 4 January and 2 June 2010, and focused on the beaching and settling of Swanbank fly ash at a range of % solids in a laboratory beaching flume measuring 2 m long, by 0.6 m wide by 0.6 m high (Figure 1). Four series of tests was carried out in the flume: (i) sub-aerially (unflooded, no constriction) to simulate backfilling of a large, unflooded underground void, (ii) sub-aerially through a constriction to simulate backfilling of a narrow, unflooded underground void, (iii) under water (flooded, no constriction) to simulate backfilling of a large, flooded underground void, and (iv) under water and a head of fly ash slurry to simulate backfilling of a closed-ended, flooded underground void.

Characterisation testing of the Swanbank fly ash was also carried out, including particle size distribution analysis, Atterberg limit testing, specific gravity determination, Emerson crumb testing, total suction determination, and pH and Electrical conductivity testing. In addition, laboratory geotechnical parameter testing was carried out, including settling column testing, undrained vane shear and drained direct shear strength testing, and oedometer testing. By way of comparison, a drained and desiccated beach at Swanbank was profiled, sampled and characterised.



(a) Schematic

(b) Constricted, under water set-up

Figure 1 UQ laboratory beaching flume

2 LITERATURE REVIEW

In the following paragraphs, Professor Williams compliments CSIRO's review of the published literature, making reference to web-based sources and unpublished information.

2.1 Effectiveness of Underground Backfilling Using Tailings

Tailings used as backfill to underground workings (http://www.tailings.info/backfill.htm), usually involving the addition of cement binder, and delivered by pipeline or borehole, can both fill voids and provide support.

2.2 Geotechnical Considerations

Sivakugan *et al.* (2006)[1] (https://www-internal.jcu.edu.au/internal/groups/public/documents/journal_article/jcuprd_049645.pdf) reported that laboratory sedimentation testing showed hydraulic fill slurry settles to a dry density (g/cm^3) of 0.6 times the specific gravity (G_s) for a wide range of tailings with specific gravity values ranging from 2.8 to 4.4. This implies that all the hydraulic fills settled to a void ratio of 0.67 and porosity of 40%. Laboratory sedimentation testing verified this. A generic ''rule of thumb'' for the particle size distribution is for a minimum of 15% of the material to be finer than 20 mm, which ensures that the surface area of the particles is large enough to provide adequate surface tension to hold the water on the solid particles and provide a very thin, permanent lubricating film. Paste fill typically shows non-Newtonian Bingham plastic flow characteristics, resulting in plug flow (batches flow in solid slugs) characteristics of the paste.

From constant head and falling head permeability tests carried out on the hydraulic fill samples, the permeability was measured to be in the range of 7 to 35 mm/h (2 x 10^{-6} to 1 x 10^{-5} m/s).

Paste fill contains at least 15% of particles finer than 20 mm, and an effective size which 10% of particles pass (D_{10}) in the order of 5 mm. The 3 to 6% binder improves the strength and thus stability significantly. The large fines content of the paste fill enables most of the water to be held to the surface of the particles, and therefore drainage is not a concern on paste backfilling.

2.3 Paste Tailings

Golder Paste Tec™ (http://www.golder.com/), a leading provider of consulting advice on cemented thickened and paste tailings for underground backfill and surface disposal (Figure 2), with projects worldwide.

Figure 2 Surface paste tailings disposal

[1] Sivakugan, N., Rankine, R.M., Rankine, K.J. and Rankine, K.S. (2006). Geotechnical considerations in mine backfilling in Australia, *Journal of Cleaner Production*, **14**, 1168-1175.

Paste is a non-segregating, non-bleeding engineered mixture of solids and water. It possesses a yield stress; produces a measurable slump (maximum of 250 mm); can be moved through a pipeline by gravity, positive displacement pump, or centrifugal pump; has no critical flow velocity; and consistently demonstrates the ability to have minimal material segregation and minimal water bleed at any stage of transport or placement.

Paste technology, while prevalent today, can trace its roots back over 30 years. It was first introduced for use in Europe in 1978, in the United States in 1980, in South Africa in 1984, in Canada in 1984, and in Australia in the 1990's. Extensive research conducted in Canadian mines in the early 1990's resulted in steady advances in the preparation and transportation of paste. Since that time, the acceptance of paste backfill plants, especially in bulk mining, has become widespread. The first paste plant built solely for the disposal of mineral tailings was constructed in 1999 and, since then, over 30 paste installations have begun operating or are in various stages of design or construction throughout the world.

Today, there are two main applications for paste technology: (i) underground backfill (utilised primarily in the mining industry but is also applicable in other industries, such as land development, where void filling is important), and (ii) surface disposal of mineral waste materials (typically mine tailings) or other industrial residues (including surface disposal of industrial mineral sludges).

The benefits of utilising paste technology in a backfill application include: (i) lower cement content, (ii) reduced requirement for drill holes, (iii) utilisation of surplus/waste materials readily available on site, (iv) complete filling of a void to the back of the opening, (v) higher strength, (vi) reduced mine dewatering, and (vii) reduced risk of in-rush.

Paste technology originated in the hard rock metal mining industry approximately 20 years ago, and the application of paste technology is now being expanded to include other large-volume waste types, such as fly ash (http://www.imwa.info/docs/BeloHorizonte/UseofPaste.pdf). Tailings paste is defined as a dense, viscous mixture of tailings and water which, unlike slurries, does not segregate when not being transported. Paste has a working consistency similar to wet concrete, and several of the geotechnical characterisation techniques have their origin in the concrete industry. Based on a large volume of empirical data and operational experience, it has been determined that a paste must contain at least 15% by mass passing 20 µm to exhibit paste flow and retain sufficient colloidal water to create a non-segregating mixture.

According to Robinsky (1999)[2], one of the pioneers of paste technology, virtually all mineral processing methodologies generate tailings amenable to paste production. When being transported either by gravity or through pumping, paste produces a plug flow, with the fine particles creating an outer annulus, thereby reducing friction. The coarse particles are forced into the centre of the conduit with the finer fraction acting as the carrier. This allows for conveyance of very coarse fragments, the size of which is only limited by the pipe diameter. Very little free water is generated from paste. In addition, the permeability of a poorly sorted, run-of-mill paste is significantly lower than that of classified, well-sorted tailings. When placed underground, the paste may represent a hydraulic barrier to groundwater flow. The reduction in free water results from two characteristics of paste: (i) colloidal retention of water and (ii) reduced infiltration relative to traditional tailings.

Several processes may combine to create the behaviour unique to paste: (i) surface phenomena (electrostatic attraction between water and charged particle surfaces); (ii)

[2] Robinsky, E.I. (1999). Thickened tailings disposal in the mining industry. *Robinsky Associates*, Toronto, 209 p.

chemical interaction between particles and water (e.g. hydrogen bonding); and (iii) physical interaction (water held under surface tension due to high capillary or matric tensile stresses). Since empirical observations have demonstrated that water retention and other paste characteristics, such as rheology, are related to the mineralogical composition of the tailings material, it appears that the chemical parameters of the tailings particles at least in part govern water-particle interaction.

Laboratory and field testing have demonstrated that the permeability of paste is generally approximately half an order of magnitude lower than that of the corresponding tailings slurry. This is primarily caused by the fact that paste is produced from run-of-mill tailings that have not undergone the particle size segregation commonly observed during tailings slurry deposition. Consequently, the paste maintains the full distribution of particle sizes, which results in the reduced permeability characteristic of poorly-sorted materials. In addition to the effect of grainsize distribution, the tensile stresses in the tailings are responsible for reduced infiltration. This occurs because the gravitational downward pull on the liquid surrounding the tailings particles is countered by upward capillary suction (Robinsky, 1999). Admixture of small amounts (e.g. 1 to 2% by mass) of binder materials with pozzolanic and/or cementitious parameters may further decrease the permeability of the paste.

2.4 Pressurised Grout Remote Backfilling

Dodd (2005)[3] (http://www.fhwa.dot.gov/engineering/geotech/hazards/mine/workshops/kdot/kansas04.cfm) reported on pressurised grout remote backfilling used for stabilising collapsing underground coal mines in North Dakota. In this technique, a cementitious (fly ash) grout is pumped through cased drill holes directly into mine cavities to fill them and thereby stabilise the surface from collapse. Fly ash is 18% cheaper than cement and it also improves flowability of the grout.

There are more than 600 abandoned coal mines in North Dakota, mostly underground mines. As these abandoned underground mines have deteriorated with time, deep collapse features, or sinkholes, have surfaced in many areas. These features are very dangerous, especially when they occur at or near residential and commercial areas and public roads. The Abandoned Mine lands (AML) Division of the North Dakota Public Service Commission (PSC) has been using remote backfilling methods in an attempt to prevent mine subsidence in high-use areas since the early 1980's.

Gravity fill remote backfilling was utilised until 1990. In this method, slurry, usually consisting principally of sand and water, was poured down drilled holes directly into the underground mined workings. Results of gravity fill remote backfilling were often unsatisfactory because the slurry could not penetrate all void areas if the mine was already partially collapsed. In addition, the slurry was not cohesive and tended to flow, to be washed away, or to settle as the water dissipated.

Since 1991, pressurised grout remote backfilling has been used. This method is effective in stabilising the surface from underground mine subsidence, especially when mined workings have begun to collapse. One of the drawbacks of the method was its high cost, mainly due to the high cost of Portland Cement. In 1995, a comprehensive grout testing research project determined that fly ash from specific sources readily available in North Dakota could be used to replace some of the cement in the grout mix. This research yielded a grout formulation that is cheaper and has better handling characteristics, yet is relatively safe.

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[3] Dodd, W.E. (2005). Fly ash use in pressurised grout remote backfilling of abandoned underground mines in North Dakota. *Interstate Technical Group on Abandoned Underground Mines Third Biennial Workshop*.

Fly ash is about 80-90% composed of glass formed from molten clays, shales, limestone, and dolomite. These small spherical particles combine with calcium hydroxide to form calcium silicate hydrate, the principal binder of cement. Fly ash is classified by its cementitious parameters by the American Society for Testing and Materials (ASTM). Fly ash is a pozzolan, which forms cement-like compounds when mixed with lime and water. Fly ash is somewhat similar to volcanic ash used to produce the earliest cements about 2,300 years ago near the Italian town of Pozzuoli.

Although most of the fly ash produced in the US is disposed of as a waste product in landfills and impoundments, it has many potentially beneficial uses. Fly ash is used in mine reclamation projects to fill surface and underground mines and to treat acid mine drainage and soils.

Since 1981, more than 85 primary reclamation projects have been completed in North Dakota at a cost of over $23 million. These projects have included backfilling dangerous surface mine pits, extinguishing mine fires, filling dangerous sinkholes resulting from collapse of underground mines, and remote backfilling to prevent collapse of underground mines beneath homes, buildings and roads.

The fly ash-grout testing project compared 23 different grout formulations with varying amounts and sources of fly ash, cement, sand, water and superplasticiser. This fly ash grout-testing project was developed to determine the most cost-effective, environmentally safe grout material available for use in reclamation of dry and wet underground coal mines. Grout formulations were evaluated for flowability, pumpability, cohesiveness (non-segregation during pumping), compressive strength, and leaching potential in water.

When used with cement, fly ash improves flowability and increases compressive strength. It improves flowability because the spherical particles act like ball bearings. This allows the grout to move more freely and the small particle size promotes better filling of voids. The cementitious behaviour of fly ash increase compressive strength. Contract specifications for grouting projects in North Dakota presently require that the unconfined compressive strength of grout be at least 150 psi (about 1,000 kPa) at 28 days. Use of fly ash also reduces shrinkage and slows set-up time, an important factor if grout pumping must be interrupted for a few hours. Another important reason for using fly ash is recycling: every tonne of fly ash used beneficially is one not disposed in a landfill.

Fly ash can potentially pose environmental and health risks. It contains trace amounts of several toxic elements including boron, molybdenum, selenium, and arsenic. These elements could contaminate soil and water. Portland cement also contains these elements and they can occur naturally in soil and water. If used responsibly, fly ash is a safe product and can be used safely with very limited chances of polluting soils or water.

After grout containing fly ash hardens it is fairly inert. Research conducted by North Dakota Public Service Commission (Wald and Beechie 1996)[4] found that grout mixes using fly ash often leached lower concentrations of trace minerals than cement-only grout. This research also indicated that, depending on the source of fly ash, leachate from hardened grout could meet safe drinking water standards for heavy metal concentrations.

[4] Wald, S. and Beechie, B. (1996). Fly ash grout testing in a simulated wet mine environment. *Proceedings of 18th Annual Conference of the Association of Abandoned Mine Lands. Kalispell, Montana, September 15-18, 1996*.

2.5 Fly Ash Paste Backfill

ACARP Project C7033 (http://www.acarp.com.au/abstracts.aspx?repId=C7033), completed in 2001 by Mike Gowan of Golder Associates Pty Ltd, considered the utilising fly ash paste backfill.

Coal reserves in the Newcastle area are being sterilised due to the risks associated with post-mining surface settlements. Selective backfill using paste fly ash has the potential to increase the reserves accessible to mining by providing an economic and environmentally acceptable backfill material. However, there has been no large-scale economically feasible use of paste backfill in coal mines anywhere in the world to date.

There is a unique opportunity in the Newcastle coal mining area to exploit the large quantities of fly ash available from the adjacent power stations to selectively backfill coal mines and open up large areas of previously sterilised coal reserves. While fly ash, combustion ashes and other mining wastes have been used for coal mine backfill, they have generally been limited in their application. Large volumes of fly ash have been used for backfill in South Africa, but like much of the other backfills, this has been as hydraulic slurry, with large volumes of supernatant water associated with the settling of the materials.

Full tailings paste backfill is being used in hard rock mines, is proving to be a viable and economic alternative to other backfill methods. Paste backfill has the following advantages over hydraulic backfill: (i) it exudes virtually no water on placement and as a result requires less water management, (ii) it requires far less underground containment preparation than hydraulic backfill; and (iii) it does not have to be placed continuously, since it has no critical flow velocity and can be left in the distribution system for some time.

Test work carried out for the Bayswater fly ash disposal system has shown that a high density fly ash slurry can be pumped a considerable distance compressive strength, flowability, stability, bearing capacity, modulus of subgrade reaction, lateral pressure, time of set, bleeding and shrinkage, density, and permeability. This study set out to confirm the suitability of fly ash to form paste mixtures and to demonstrate how they can be used as a successful backfill. Backfills are being used overseas for a number of purposes, including thick seam, bord and pillar and longwall mining operations. This study proposes to demonstrate, through a number of critical stages, how this experience can be adapted to the Australian conditions with the use of fly ash as the backfill material. It is intended that this study will lead to the general application of backfill using a range of materials, potentially including coal washery rejects.

2.6 Flowable Fly Ash Fill

Coal fly ash can be used as a component in the production of flowable fill, which is used as self-levelling, self-compacting backfill material in lieu of compacted earth or granular fill (http://www.tfhrc.gov/hnr20/recycle/waste/cfa56.htm). Flowable fill includes mixtures of Portland cement and filler material and can contain mineral admixtures, such as fly ash. Filler material usually consists of fine aggregate (in most cases, sand), but some flowable fill mixes may contain approximately equal portions of coarse and fine aggregates, such as fly ash.

There are two basic types of flowable fill mixes that contain fly ash: (i) high fly ash content mixes, and (ii) low fly ash content mixes. The high fly ash content mixes typically contain nearly all fly ash, with a small percentage of Portland cement and enough water to make the mix flowable. Low fly ash content mixes typically contain a high percentage of fine aggregate or filler material (usually sand), a low percentage of fly ash and Portland cement, and enough water to also make the mix flowable.

Since flowable fill is normally a comparatively low-strength material, there are no strict quality requirements for fly ash used. Its fine particle sizing (non-plastic silt) and spherical particle shape enhances mix flowability. Its relatively low dry unit weight (usually from 0.89 to 1.3 g/cm^3) assists in producing a relatively lightweight fill, and its pozzolanic nature provide for lower cement requirements than would normally be required to achieve equivalent strengths.

The engineering parameters of fly ash, including compressive strength, flowability, stability, bearing capacity, lateral pressure, time of set, bleeding and shrinkage, density, and permeability, that are the most influential in its performance in flowable fill mixtures are its spherical particle shape and its pozzolanic activity with Portland cement.

Strength development in flowable fill mixtures is directly related to the cement and water contents. Most high fly ash content mixes only require from 3 to 5% Portland cement by dry mass of fly ash to develop 28-day compressive strengths from 500 to 1,000 kPa, while low fly ash content mixes may not require Portland cement. As the water content is increased to produce a more flowable mix, compressive strength development will probably be somewhat lowered.

Flowability is a measure of how well a mixture will flow on placement. The higher the water content, the more flowable the mix. Flowability can be measured using a standard concrete slump cone, with the slump varying between 150 mm and 200 mm. For high fly ash content flowable fill mixes, the slump is at least 25 to 50 mm higher than for low fly ash content mixes at comparable moisture contents. Admixtures (such as water reducing agents) are not normally used in flowable fill.

For low fly ash content flowable fill materials, triaxial strength tests indicate a friction angle of 20° for mixes containing fine sand, and up to 30° for mixes containing concrete sand. Cohesion measured from triaxial testing varies with the compressive strength. Mixes with a 350 kPa compressive strength have 120 kPa cohesion, while mixes with 700 kPa compressive strength have 200 kPa cohesion.

The allowable bearing capacity of hardened flowable fill has been shown to vary directly with compressive strength and friction angle. For example, the allowable bearing capacity for flowable fill with a compressive strength of 700 kPa may range from 80 t/m^2 at a 20° friction angle to 160 t/m^2 at a 30° friction angle; i.e., two to four times the bearing capacity of most well-compacted granular soil fill materials.

Because of lateral fluid pressure at the time of placement, flowable fill is generally placed in lifts not exceeding 1.2 to 1.5 m. Theoretically, once flowable fill placed against a retaining wall or abutment has hardened, the lateral fluid pressure exerted during placement and initial curing should be significantly reduced. Limited load cell instrumentation of flowable fill abutment backfills has shown that flowable fills exert lateral pressure similar to that of granular materials.

For most flowable fill mixes, especially those with high fly ash contents, an increase in the cement content or a decrease in the water content, or both, should result in a reduction in the hardening time. Typical high fly ash content flowable fill mixes (containing 5% cement) harden sufficiently to support the weight of an average person in about 3 to 4 hours, depending on the temperature and humidity. Within 24 hours, construction equipment can operate safely on the surface. Some low fly ash content flowable fill mixes, especially those containing self-cementing fly ashes, can carry load within 1 to 2 hours of placement.

High fly ash content flowable fill mixes with relatively high water contents tend to release some bleed water prior to initial setting. Evaporation of the bleed water often results in a shrinkage of approximately 1% of the flowable fill depth. Shrinkage may occur laterally as well as vertically. No additional shrinkage or long-term settlement of flowable fill occurs once the material has reached an initial set. Low fly ash content mixes, because of their high fine aggregate content and ability to more readily drain water through the flowable fill, tend to exhibit less bleeding and shrinkage than high fly ash content mixes.

High fly ash content flowable fill mixes are usually less dense than compacted natural soils, with wet densities ranging from 1.46 to 1.95 g/cm^3 (the first-placed material being densest). Low fly ash content flowable fill mixes have wet densities ranging from 1.79 to 2.19 g/cm^3. Significant decreases in density (as low as 0.33 kg/m^3) have been achieved in high fly ash content flowable fill mixes by the use of foaming agents in proprietary mixtures for the purposes of load reduction.

Permeability values for high fly ash content flowable fill mixtures decrease with increasing cement content and are generally in the range from 10^{-8} to 10^{-9} m/s. Although few data are available regarding the permeability of low fly ash content flowable fill mixtures, the permeability of such mixtures is greater than that of high fly ash content mixtures, in the range from 10^{-6} to 10^{-8} m/s.

2.7 Fly Ash Mine Backfill in Australia and Overseas

Ward *et al*. (2006)[5] reviewed fly ash open cut and underground mine backfill practice in Australia. The review included the geotechnical and geochemical characterisation of a range of Australian fly ash materials, overseas fly ash, the interaction of fly ash with water, regulatory issues, the environmental impact of fly ash emplacement, fly ash mine backfill, and other applications. The review concluded that there has been limited fly ash mine backfill in Australia and that there is considerable potential for an increase.

[5] Ward, C.R., French, D., Jankowski, J., Riley, K. and Li, Z. (2006). Use of coal ash in mine backfill and related applications. *Research Report 62*, CRC for Coal in Sustainable Development, QCAT.

3 TESTING METHODOLOGY

The testing was carried out on fly ash from Swanbank Power Station, and comprised (i) laboratory characterisation testing of the fly ash at UQ, (ii) flume testing of slurried fly ash at UQ, and (iii) field testing, profiling, and sampling and testing at UQ, of an old fly ash beach at Swanbank Power Station. Three 200 l drum samples of fly ash were initially collected from a stockpile at Swanbank Power Station for the laboratory testing at UQ (Figure 3). These were later supplemented with two additional drum samples from the same source to enable additional laboratory flume tests to be carried out.

Figure 3 Sampling Swanbank fly ash for laboratory testing

3.1 Laboratory Characterisation Testing

Laboratory characterisation testing of the three initial drum samples of Swanbank fly ash, carried out in accordance with AS 1289 Methods of Testing Soils for Engineering Purposes where appropriate, included as-sampled total moisture content (= [mass of water]/[mass of solids + water, or 100 - % solids], expressed as a %; this is the conventional expression for moisture content used in the mining context) and total suction testing (using a WP4 Dewpoint Potential Meter), particle size distribution analysis by sieving (dry and dispersed) and hydrometer, Atterberg Limit testing (three replicates), specific gravity determination (by pychnometer using helium), Emerson crumb testing (three replicates), and pH and Electrical conductivity testing. The Electrical Conductivity values were used to estimate the as-sampled osmotic suctions, from which the matric suction was determined by subtraction from the measured total suctions.

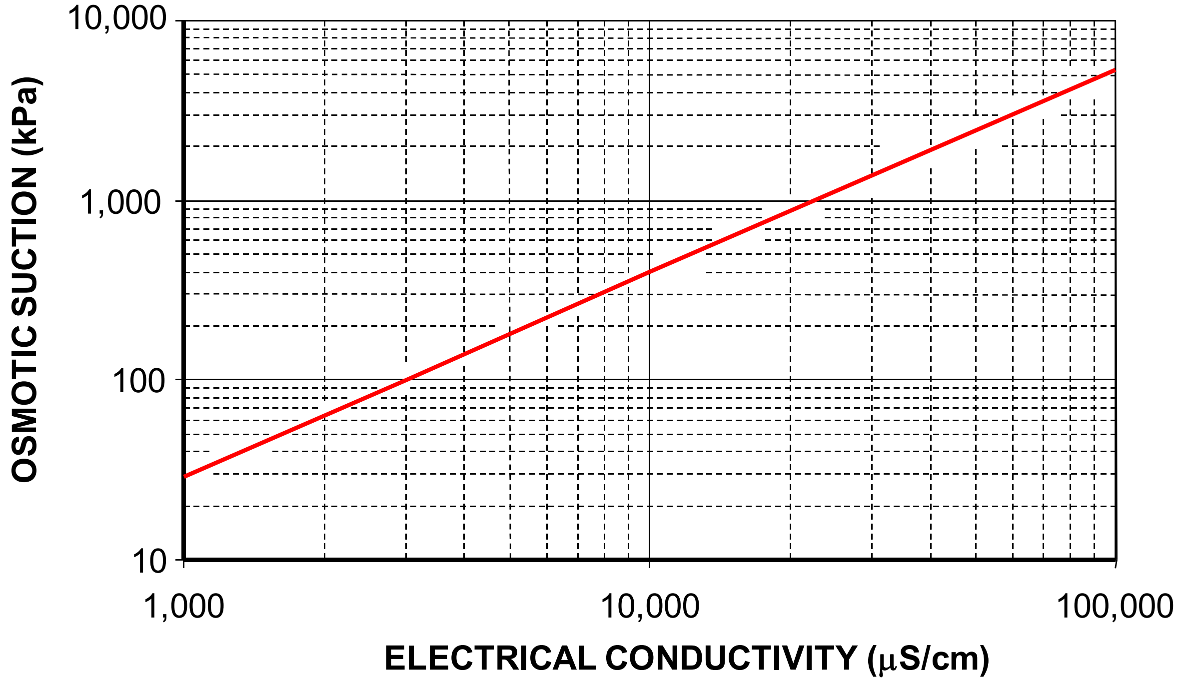

Figure 4 Correlation between osmotic suction and Electrical Conductivity (at 25oC; after USDA, 1954)[6]

3.2 Laboratory Geotechnical Parameter Testing

Laboratory geotechnical parameter testing of the Swanbank fly ash, carried out in accordance with AS 1289 where appropriate, included settling column testing, undrained vane shear and drained direct shear strength testing, and oedometer testing.

The settling column tests were carried out in 1,000 cm^3 measuring cylinders on Swanbank fly ash at initial % solids of 55%, 50%, 45% and 35%, and the surface of the settling solids was monitored over time until settling ceased. The data collected were then used to determine average % solids, total moisture content, and dry density plots with time.

The undrained vane shear strength test was carried out on Swanbank fly ash placed in a CBR mould at an initial % solids of 50% and maintained under water, and the strength was tested with time at about 50 mm depth below the surface of the settling solids using a miniature shear vane measuring 12.7 mm in diameter and 12.7 mm in height. The drained direct shear strength test was carried out on saturated Swanbank fly ash placed in a 60 mm direct shear box at an initial % solids of 50%, and sheared under a normal stress of 1.5 kPa (top cap only) at a slow rate of 1.5 mm/hour (0.063 mm/min) to ensure drained conditions.

The oedometer test was carried out in a standard 76 mm diameter ring on Swanbank fly ash at an initial % solids of 50%, under applied stresses of 1 kPa, 10 kPa, 20 kPa, 50 kPa and 100 kPa, each left in place until primary consolidation had ceased.

[6] USDA. (1954). *Agricultural Handbook No. 60, Diagnosis and Improvement of Saline and Alkali Soils*. L.A. Richards (ed.). United States Dept of Agriculture.

3.3 Laboratory Flume Testing

Beaching and settling tests using Swanbank fly ash slurry were carried out at a range of % solids in the 2 m long UQ laboratory flume shown in Figure 1. Four series of tests was carried out in the flume: (i) sub-aerially (unflooded, no constriction) to simulate backfilling of a large, unflooded underground void, (ii) sub-aerially through a constriction to simulate backfilling of a narrow, unflooded underground void, (iii) under water (flooded, no constriction) to simulate backfilling of a large, flooded underground void, and (iv) under water and a head of fly ash slurry to simulate backfilling of a closed-ended, flooded underground void.

The fly ash slurry was prepared by mixing dried fly ash with tap water to the required % solids using a mechanical mixer. Sufficient slurry was prepared in advance in 20 l buckets for each flume test. Prior to introducing the slurried fly ash into the delivery funnel of the flume, each bucket was re-mixed using the mechanical mixer. Buckets of slurry were then poured into the flume as continuously as possible.

For the unflooded beach tests, the lip at the end of the flume was a nominal 5 mm high, and fly ash delivery was continued until slurried fly ash just started to overflow this lip into a collector and thence to a spare 20 l bucket, to develop a beach profile along the full length the flume. A number of unflooded flume tests was carried out with a constriction over the central third of the flume length, to simulate an underground bord and pillar opening. The constriction was formed by two 50 mm high polystyrene blocks placed either side of the flume to halve the width through which the slurried fly ash had to pass. They were held down with a sheet of Perspex. For the flooded beach tests, the lip at the end of the flume was raised to a nominal 50 mm and the flume pre-filled with tap water. These tests were continued until fly ash solids reached the end of the flume, and stopped before they overflowed the raised end lip of the flume.

To simulate a pair of closed-ended bord and pillar openings, a central 50 mm high polystyrene block covering half the width of the flume and extending over the lower two-thirds of its length was placed in the base of the flume, and covered with a sheet of Perspex sealed to the sides and end of the flume. In order to apply a head of fly ash slurry to the constricted, closed-ended flume, a Perspex divider was placed above the constriction to the top of the flume (Figure 5).

Figure 5 Laboratory flume showing central constriction topped with Perspex, and Perspex divider

After allowing sufficient time (usually overnight) for the deposited fly ash solids to settle out on the beach, the longitudinal beach profile was measured at quarter points across the width of the flume (each set of these were similar, and only the central beach profiles are reported herein). The average depth of the settled out unflooded beach was between about 2 mm and 20 mm, depending on the % solids tested and hence the beach slope and, to a much lesser degree, whether or not a constriction was in place. The average depth of the settled out unconstricted flooded beaches was between about 20 mm and 35 mm, depending on the % solids tested and hence the beach slope.

3.4 Field Beach

A typical fly ash slurry beach at Swanbank Power Station is shown in Figure 6. The fly ash is understood to be delivered at a nominal % solids of about 15% by mass. A dried beach was levelled and sampled for total moisture content determination at approximately 25 m intervals over its 355 m length.

Figure 6 A typical fly ash slurry beach at Swanbank Power Station

4 TEST RESULTS AND INTERPRETATION

The test results and their interpretation are given in the following sections.

4.1 Laboratory Characterisation of Swanbank Fly Ash

Laboratory characterisation testing of Swanbank fly ash carried out at UQ included total moisture content determination, particle size distribution analysis, Atterberg limit testing, specific gravity determination, Emerson crumb testing, total suction determination, and pH and Electrical conductivity testing. The as-supplied moisture state of the samples is given in Table 1.

Table 1 As-sampled moisture state of Swanbank fly ash

PARAMETER	SAMPLE 1	SAMPLE 2	SAMPLE 3	AVERAGE
Total moisture content (%)	28.7	29.1	26.6	**28.1**
% solids by mass	71.3	70.9	73.4	**71.9**
Total suction (kPa)	20	110	60	**63.3**

Figure 7 shows the range of particle size distribution curves obtained for the three drums of Swanbank fly ash initially sampled. The addition of dispersant (in accordance with the AS 1289 standard method) prior to sieving is seen to increase the fines content (silt and clay-size) by about 5% by mass. This is due to the washing of fines off the coarser particles. Dispersant was also added to the fines prior to hydrometer analysis, and this analysis indicated a higher fines content still (by about a further 5%), although some of this apparent increase may be due to hindered settling. Emerson crumb testing of all three replicates of all three drum samples gave an Emerson Class No. of 6 for all tests, indicating a medium potential for erosion.

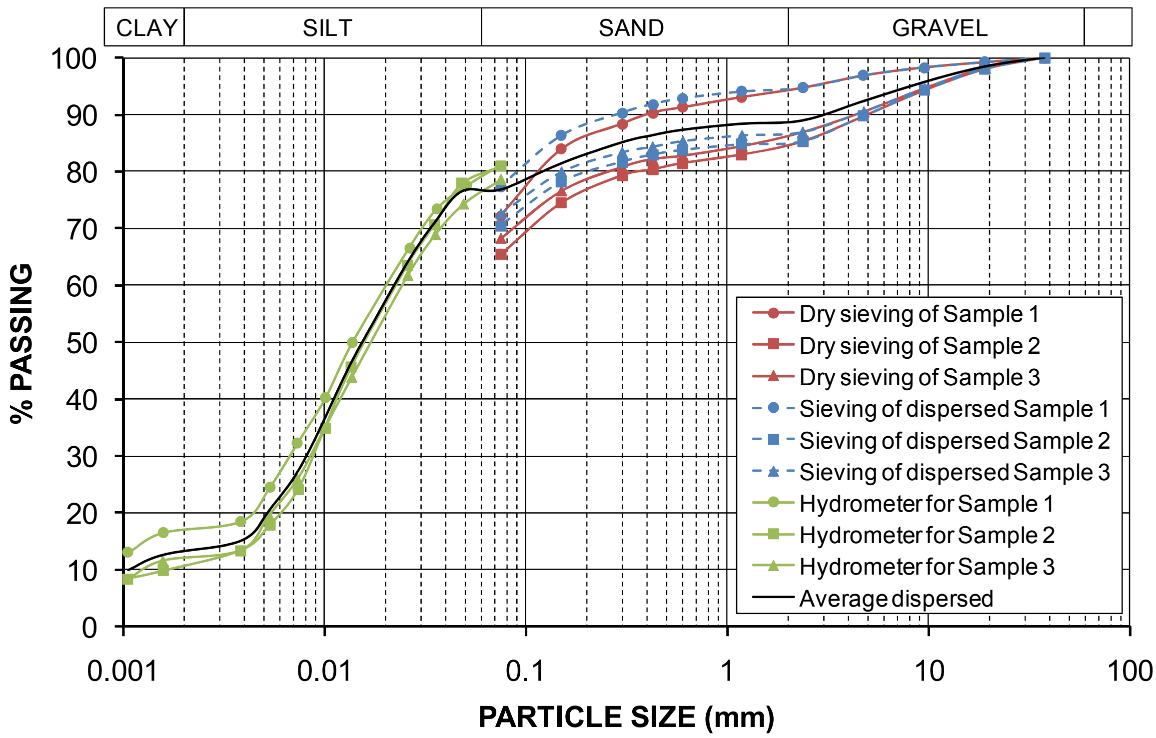

Figure 7 Particle size distribution curves for Swanbank fly ash

The Atterberg Limit test results for Swanbank fly ash are given in Table 2. According to the particle size distribution data, Swanbank fly ash classifies as a Gravelly, Clayey, Sandy SILT, while according to the Atterberg Limit data it classifies as a CL (Gravelly, Sandy, Silty CLAY of low plasticity), although the former is a better description.

Table 2 Atterberg Limit test results for Swanbank fly ash

SAMPLE	LIQUID LIMIT = PLASTICITY INDEX (Non-Plastic)			
	Replicate 1	Replicate 2	Replicate 3	Averages
1	45	45	42	**44.0**
2	50	46	48	**48.0**
3	44	47	44	**45.0**
Averages	**44.1**	**47.7**	**45.3**	**45.7**

Table 3 shows that the specific gravity of the Swanbank fly ash solids averages 2.09, substantially less than that of normal mineral matter (being 2.65 to 2.7).

Table 3 Specific gravity test results for Swanbank fly ash

SAMPLE	SPECIFIC GRAVITY
1	2.08
2	2.11
3	2.07
Average	**2.09**

Table 4 shows the (alkaline) pH and (moderate) Electrical Conductivity values obtained for Swanbank fly ash, together with the calculated osmotic and matric suctions (refer also to the total suction values given in Table 1). Figure 8 shows a plot of the total moisture content and suction values obtained for the Swanbank fly ash drum samples, which fell in the relatively narrow ranges of 36 to 41% and 10 to 100 kPa, respectively.

Table 4 pH and Electrical Conductivity test results, and calculated osmotic and matric suctions, for Swanbank fly ash

SAMPLE	pH	ELECTRICAL CONDUCTIVITY (µS/cm)	CALCULATED OSMOTIC SUCTION (kPa)	CALCULATED MATRIC SUCTION (kPa)
1	9.01	381	9.7	20 – 9.7 = 10.3
2	9.14	332	8.3	110 – 8.3 = 101.7
3	9.02	340	8.5	60 – 8.5 = 51.5
Averages	**9.09**	**351**	**8.8**	**54.5**

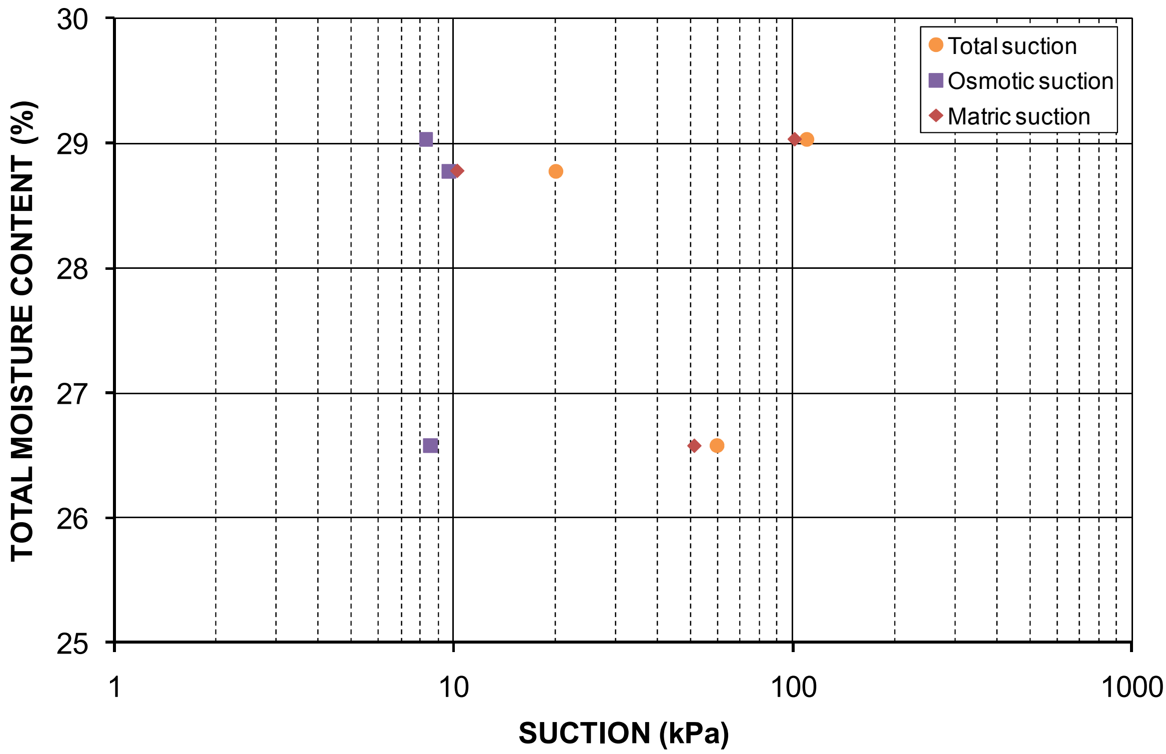

Figure 8 Total moisture content vs. Suction for Swanbank fly ash drum samples

4.2 Laboratory Geotechnical Parameters for Swanbank Fly Ash

Laboratory geotechnical parameter testing of Swanbank fly ash carried out at UQ included settling column testing, undrained vane shear and drained direct shear strength testing, and oedometer testing, the results of which are presented in the following sections.

4.2.1 Settling Column Testing Results

The results of the settling column tests are presented in the form of Time and Log_{10} (Time) plots of height of solids, average % solids, average total moisture content, and average dry density, in Figures 9 to 12, and the results are summarised in Table 5.

Table 5 Initial and final average % solids, total moisture content, dry density, and wet density on column settling of Swanbank fly ash from a slurry

% SOLIDS		TOTAL MOISTURE CONTENT (%)		DRY DENSITY (g/cm^3)		WET DENSITY (g/cm^3)	
Initial	Final	Initial	Final	Initial	Final	Initial	Final
55	64.9	45	35.1	0.771	0.980	1.402	1.511
50	66.7	50	33.3	0.676	1.022	1.352	1.533
45	68.0	55	32.0	0.588	1.053	1.307	1.549
35	72.2	65	27.8	0.428	1.157	1.223	1.604

For all % solids tested (55%, 50%, 45%, and 35%), settling is complete within 150 to 300 minutes. The final % solids increases with decreasing initial % solids (64.9% solids from 55% solids initially to 72.2% solids from 35% solids initially), as does the dry density, while the final total moisture content decreases with decreasing initial % solids. The initial and final wet densities (which drive settling) vary least with initial % solids.

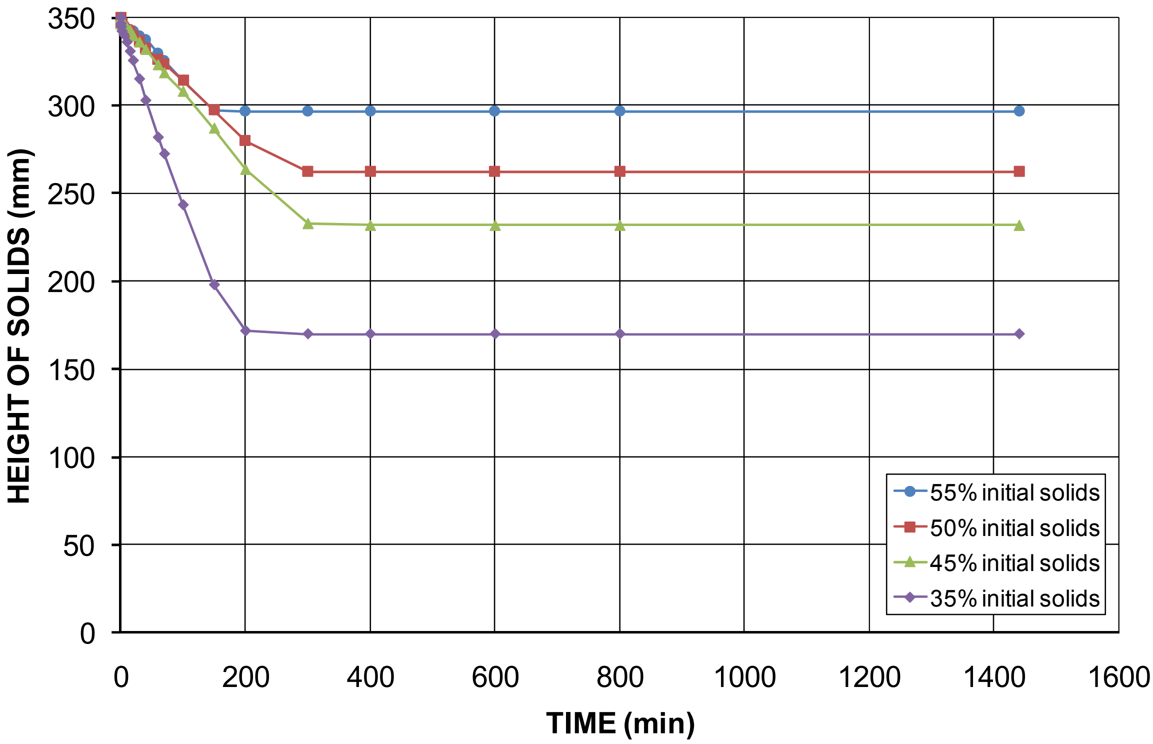

Figure 9 Settlement of Swanbank fly ash solids vs. Time for various initial % solids

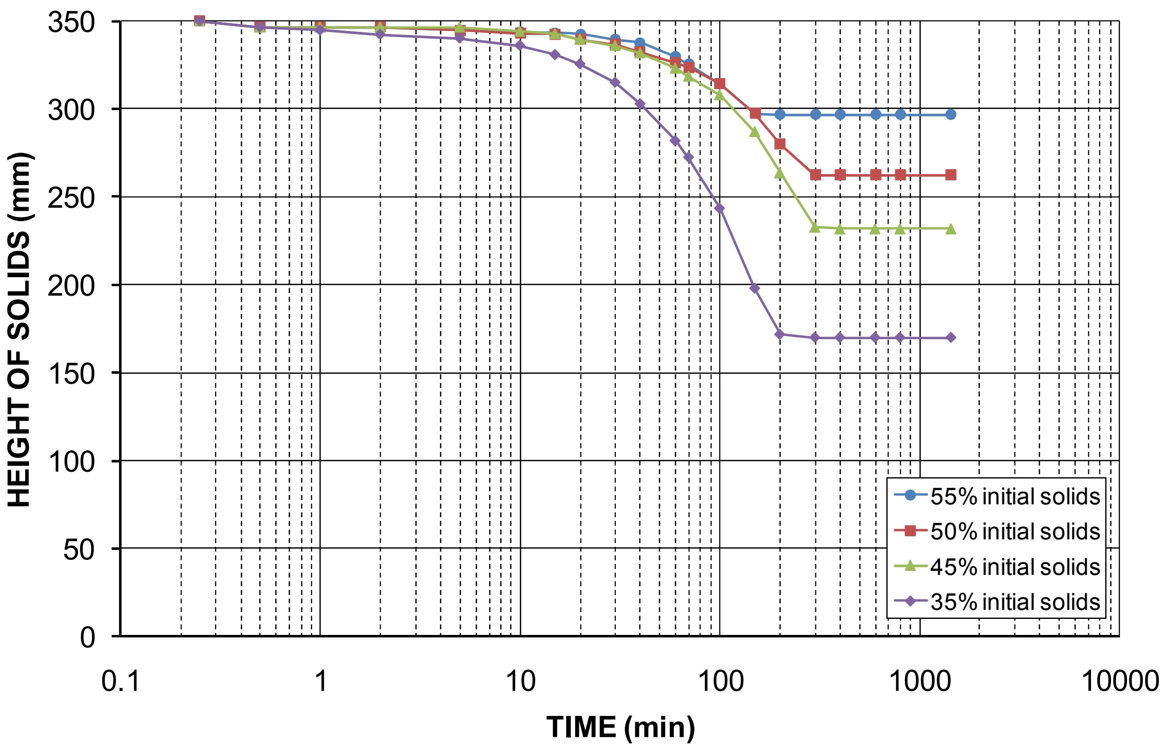

Figure 10 Settlement of Swanbank fly ash solids vs. Log_{10} (Time) for various initial % solids

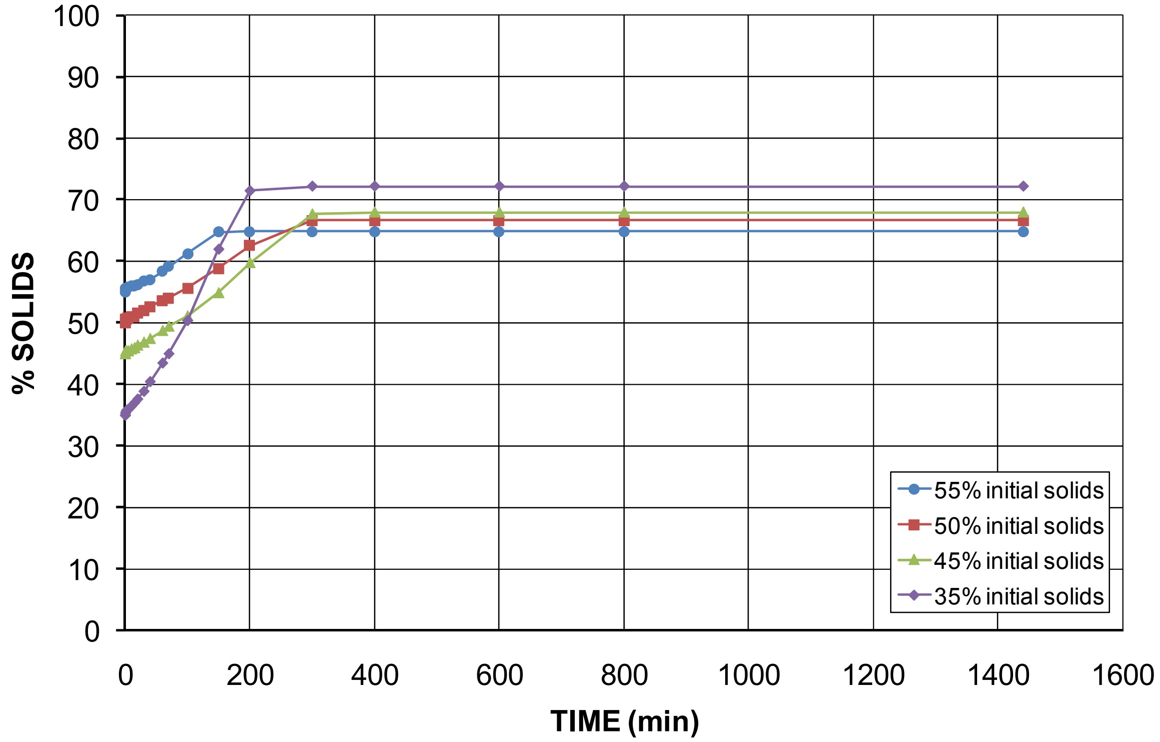

Figure 11 Average % Solids of settling Swanbank fly ash solids vs. Time for various initial % solids

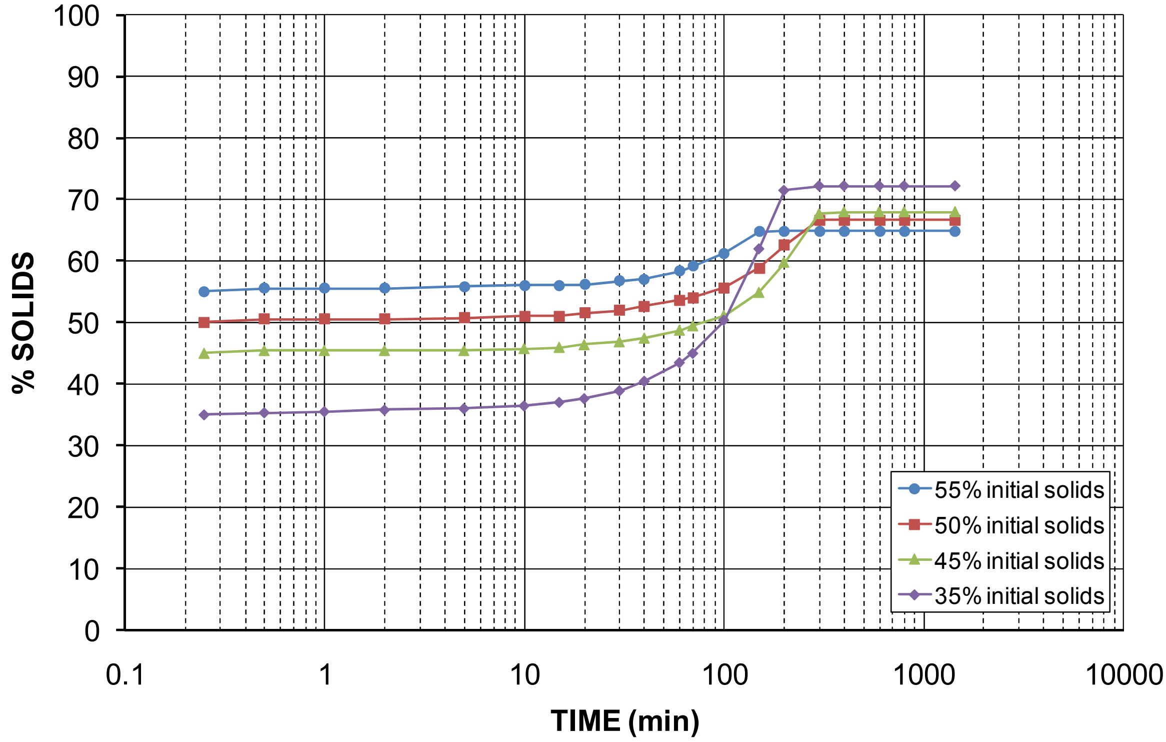

Figure 12 Average % Solids of settling Swanbank fly ash solids vs. Log_{10} (Time) for various initial % solids

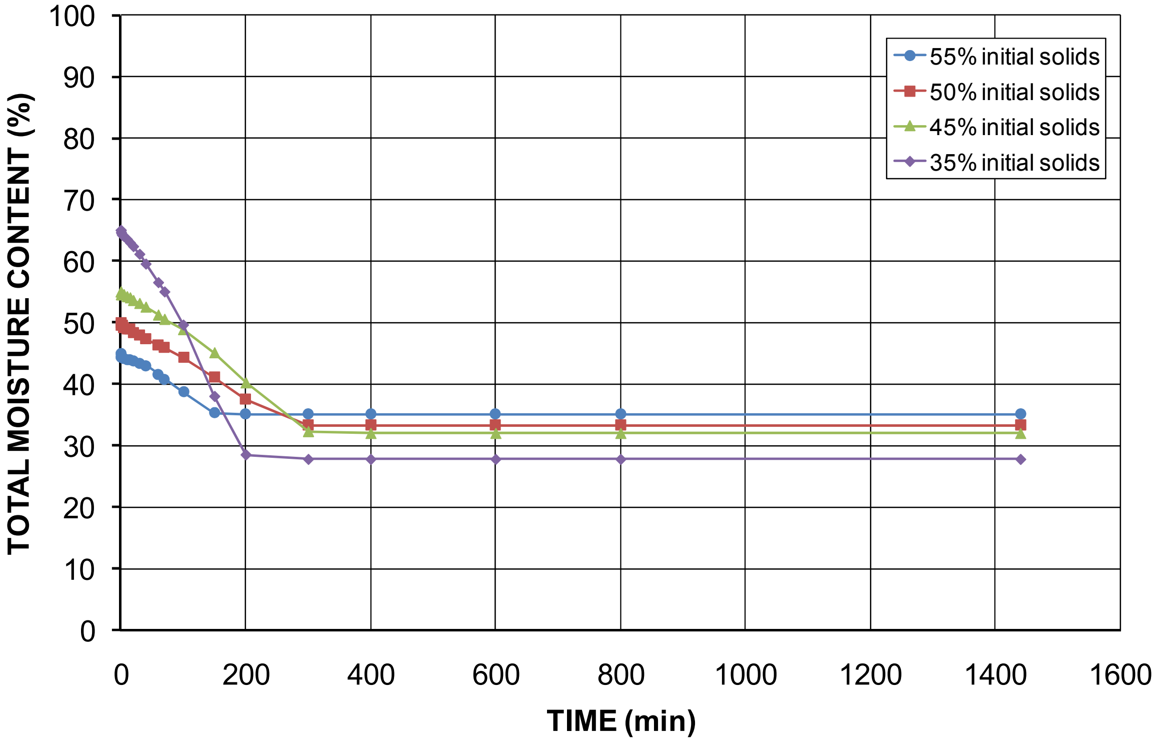

Figure 13 Average total moisture content of settling Swanbank fly ash solids vs. Time for various initial % solids

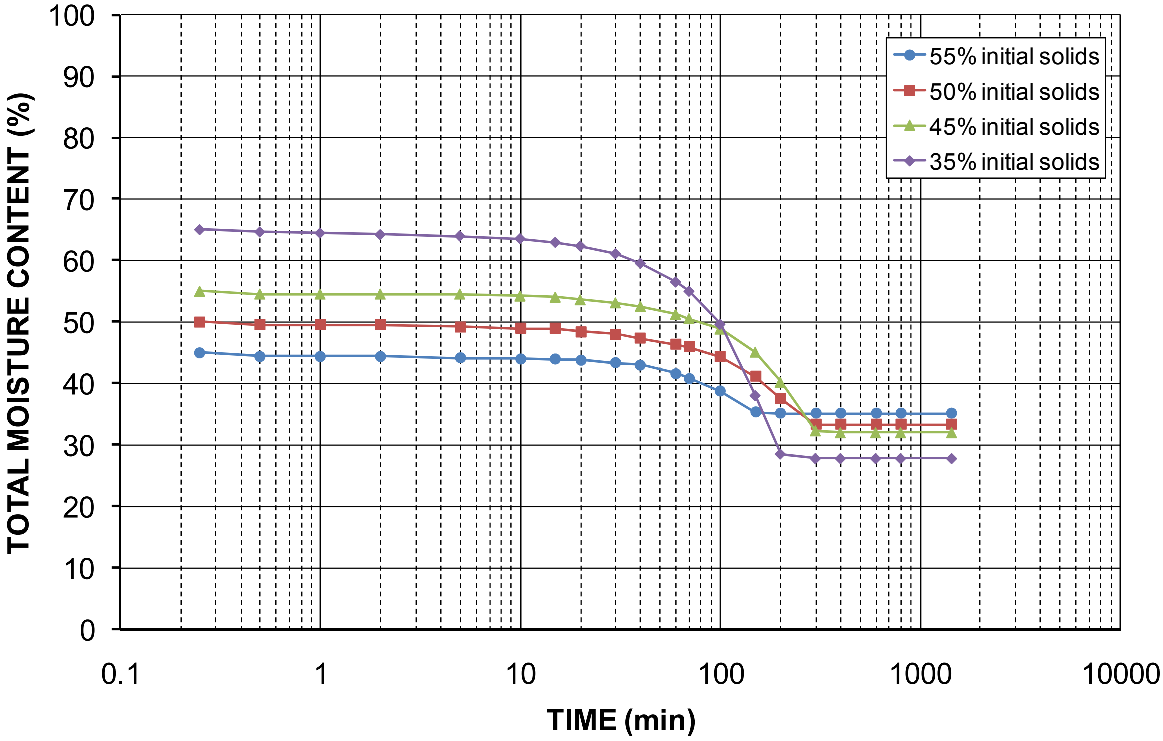

Figure 14 Average total moisture content of settling Swanbank fly ash solids vs. Log_{10} (Time) for various initial % solids

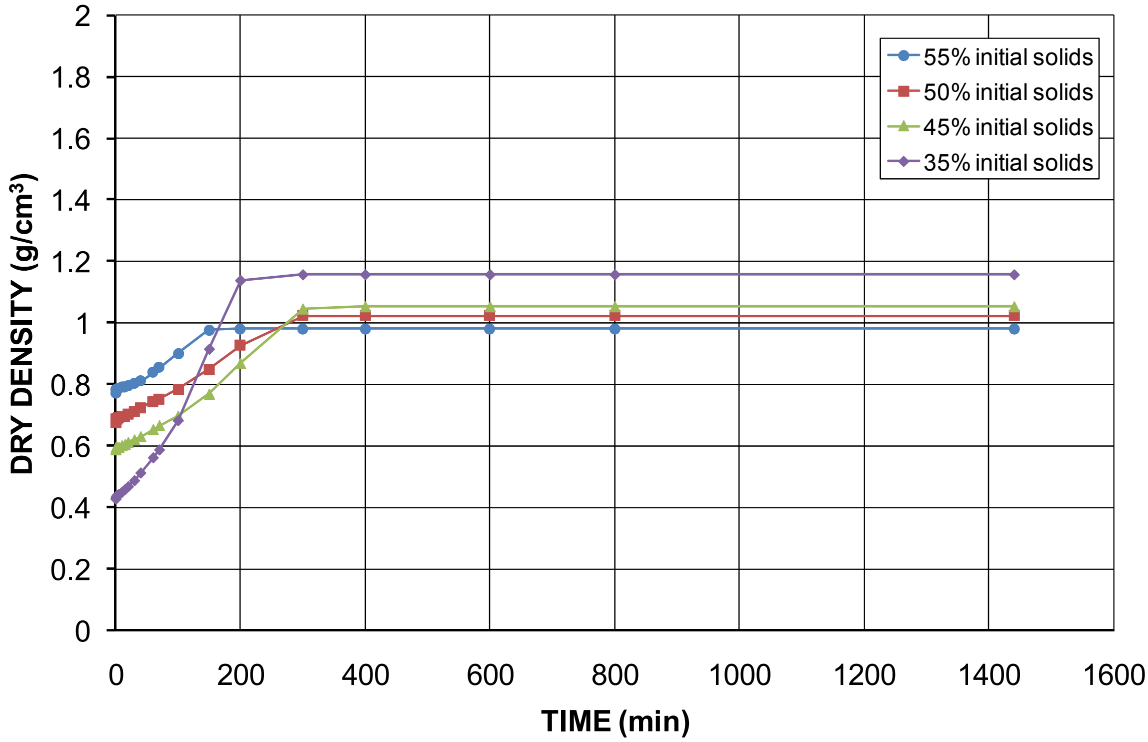

Figure 15 Average dry density of settling Swanbank fly ash solids vs. Time for various initial % solids

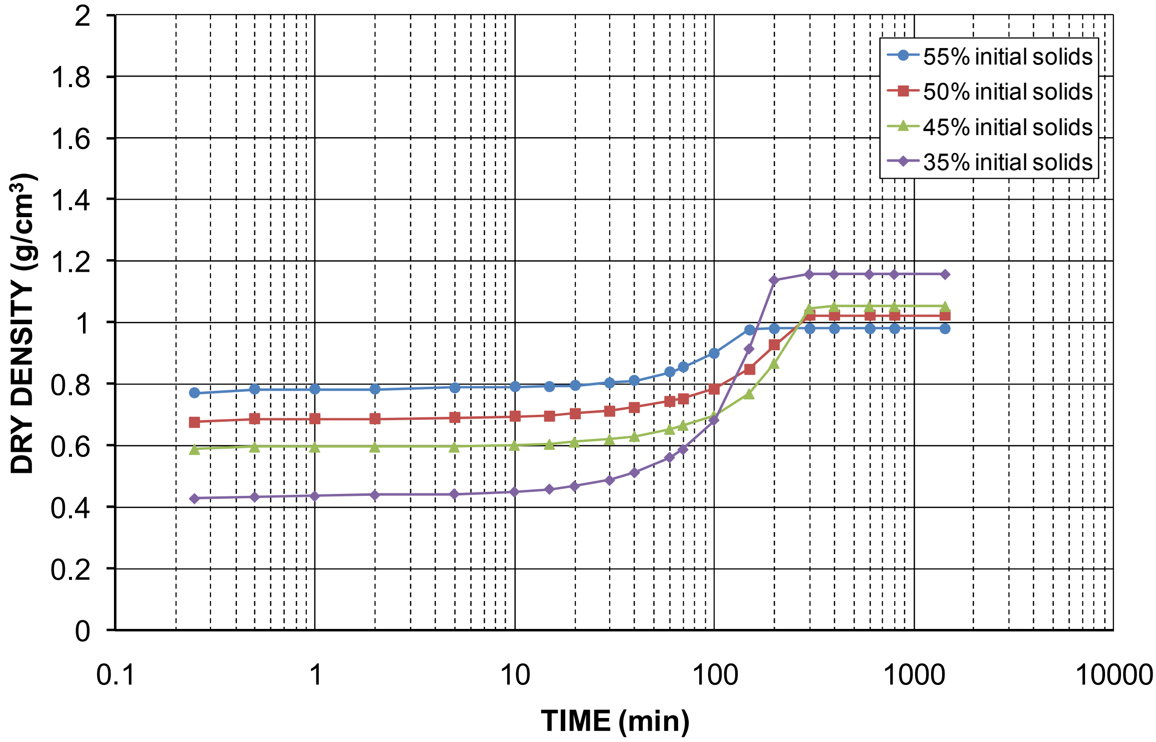

Figure 16 Average dry density of settling Swanbank fly ash solids vs. Log_{10} (Time) for various initial % solids

4.2.2 Undrained Vane Shear Strength

The result of the undrained vane shear strength testing with time of Swanbank fly ash from an initial % solids of 50% are shown in Figure 17. The testing was carried out at about 50 mm depth below the surface of the settling solids, which explains the drop off in vane shear strength with time from a peak value of about 1 kPa to about 0.6 kPa, since the upper zone is less well consolidated, and the coarser particles would have settled deeper leaving finer particles close to the surface.

The undrained shear strength of a settling slurry maintained under water is governed by its specific gravity, and hence is zero at the surface and would increase at about 1.2 kPa/m depth (for the specific gravity of Swanbank fly ash of 2.09, given that is increases at about 1.5 kPa/m depth for a normal specific gravity of 2.65). Hence, a fully-consolidated undrained shear strength of about 0.06 kPa would be expected at 0.05 m depth. In fact, higher values were obtained. This is most probably due to the presence in the fly ash of about 25% sand and gravel-sized particles, whose effect would diminish as they settled out below the depth of testing.

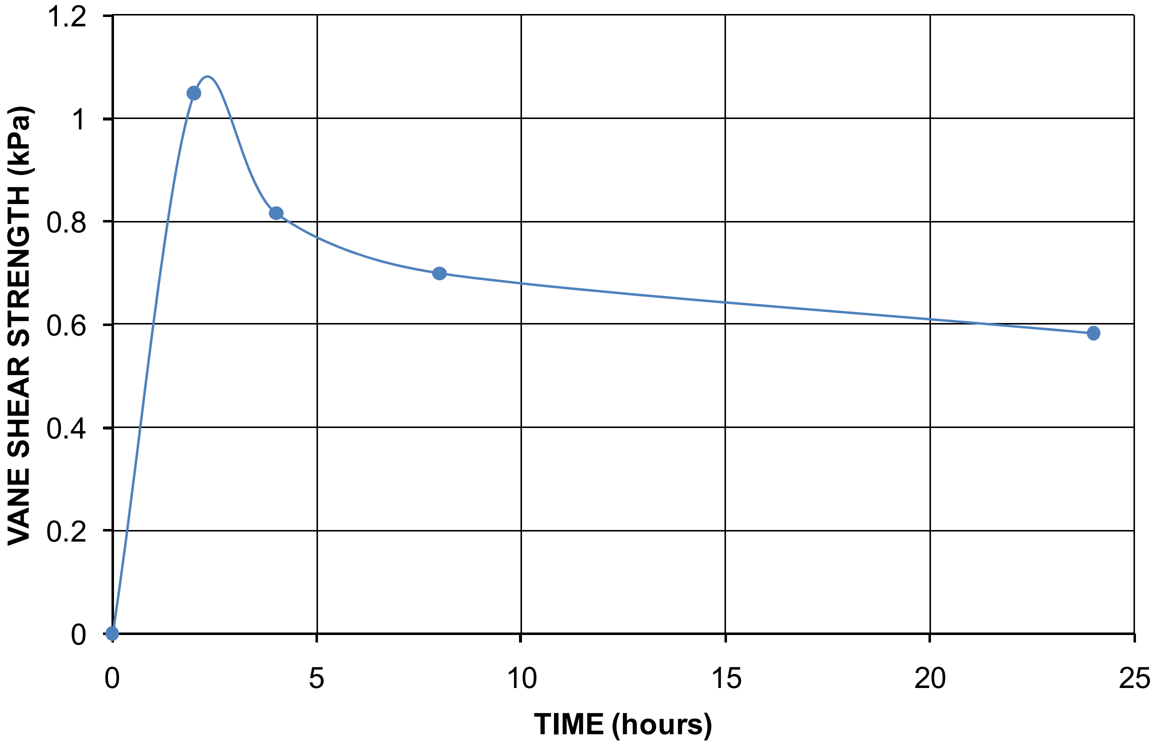

Figure 17 Undrained vane shear strength of settling Swanbank fly ash solids vs. Time

4.2.3 Drained Direct Shear Strength

The results of the drained direct shear strength testing of saturated Swanbank fly ash placed initially at 50% solids and sheared under a normal load of 1.5 kPa at a rate of 1 mm/min are presented in Figures 18 and 19. The sample settled during shearing, to a final average % solids of 61.7%, and achieved a drained friction angle of about 11.4°, and a dilation angle ($\tan^{-1}$ [increase in volumetric strain/change of shear strain]) of 1.8°. If the sample were tested under a normal pressure representing a height (or head) of additional fly ash, it would drain and consolidate, and the friction would rise, ultimately to a fully-consolidated drained friction angle in the range from 35 to 45°, and a dilation angle of the order of 30°.

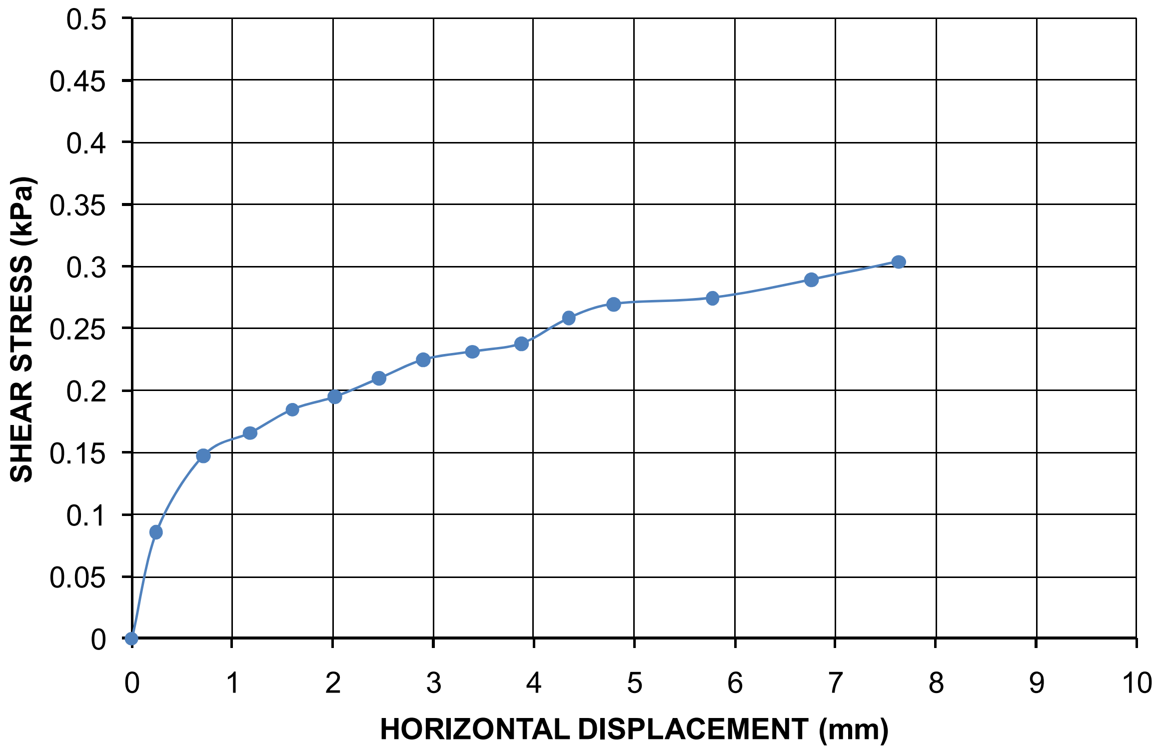

Figure 18 Direct shear box shear strength of settled Swanbank fly ash solids vs. Horizontal displacement

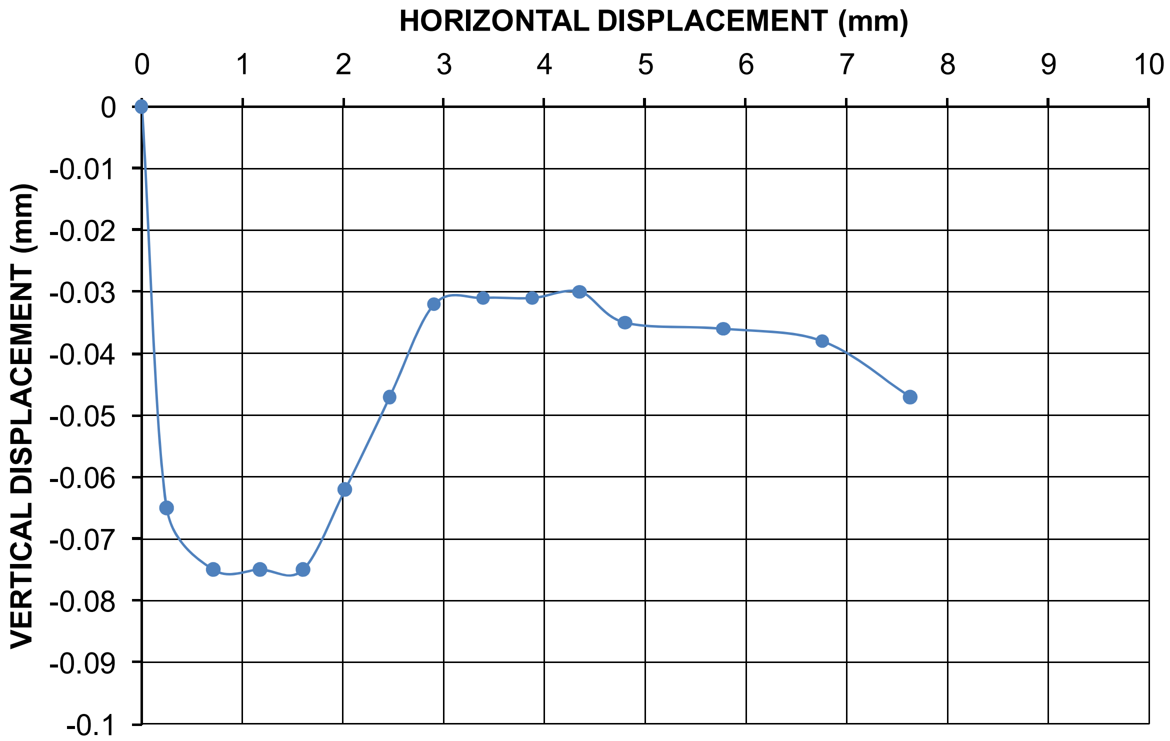

Figure 19 Direct shear box vertical displacement (settlement) of settled Swanbank fly ash solids vs. Horizontal displacement

4.2.4 Oedometer Test Results

The end-points of the oedometer test effective stress increments applied to Swanbank fly ash initially at 50% solids (initial void ratio e_0 of 2.09) are shown in Figure 20, from which a Compression Index C_c of 0.0455 is calculated.

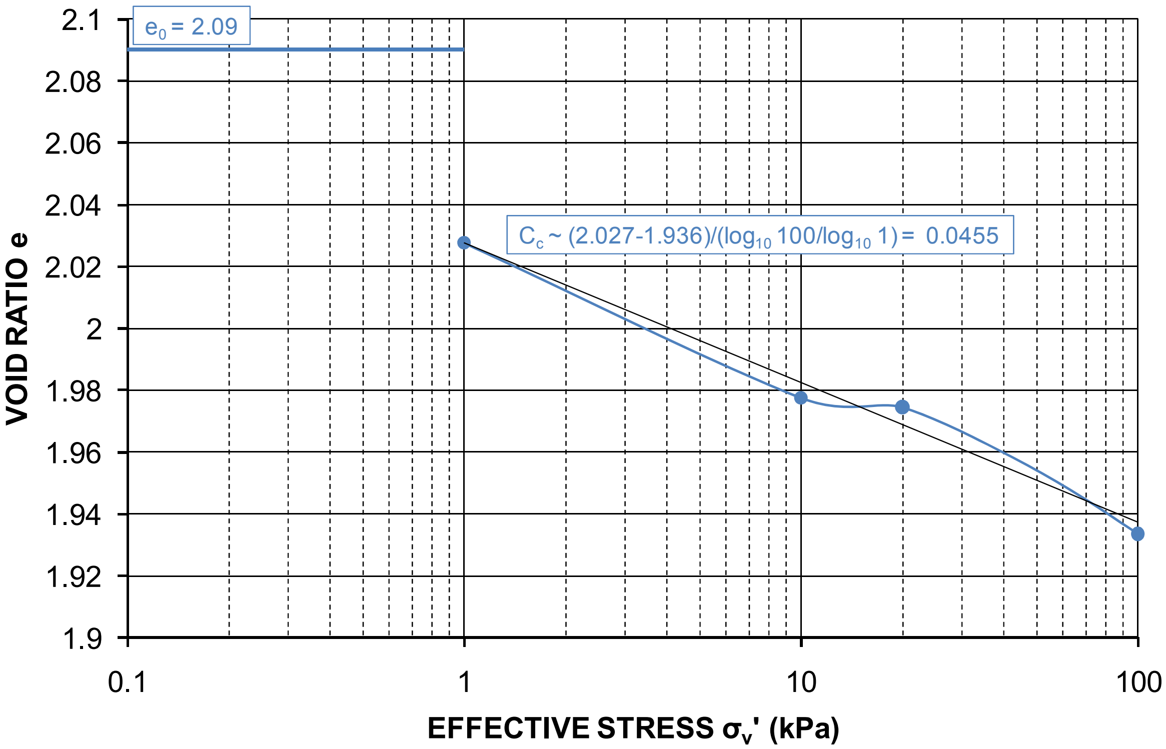

Figure 20 Oedometer plot of Void ratio vs. Effective stress for settled Swanbank fly ash

A commonly-used approximation for calculating the Compression Index of clayey soils is:

$$C_c \sim 0.009\ (LL-10) \quad [1]$$

where LL = Liquid Limit in %. For the measured average LL of Swanbank fly ash of 45.7% (Table 2), Equation [1] suggests a C_c value of 0.32, and C_c values > 0.3 are typically quoted for soft clays. The measured C_c value of 0.0455 for Swanbank fly ash is very much lower than typical values for soft clays, which may be explained by the high silt, sand and gravel-size fractions of Swanbank fly ash.

The settlement-time data obtained for each effective stress increment are plotted in terms of Log_{10} (Time) and √Time in Figures 21 and 22, respectively. From these plots, the Coefficients of Consolidation c_v may be estimated by graphical means. From the Settlement versus Log_{10} (Time) plot, c_v is given by:

$$c_v = 0.196\ (d^2/t_{50}) \quad [2]$$

From the Settlement versus √Time plot, c_v is given by:

$$c_v = (\pi/4)\ (d^2/t_1) \quad [3]$$

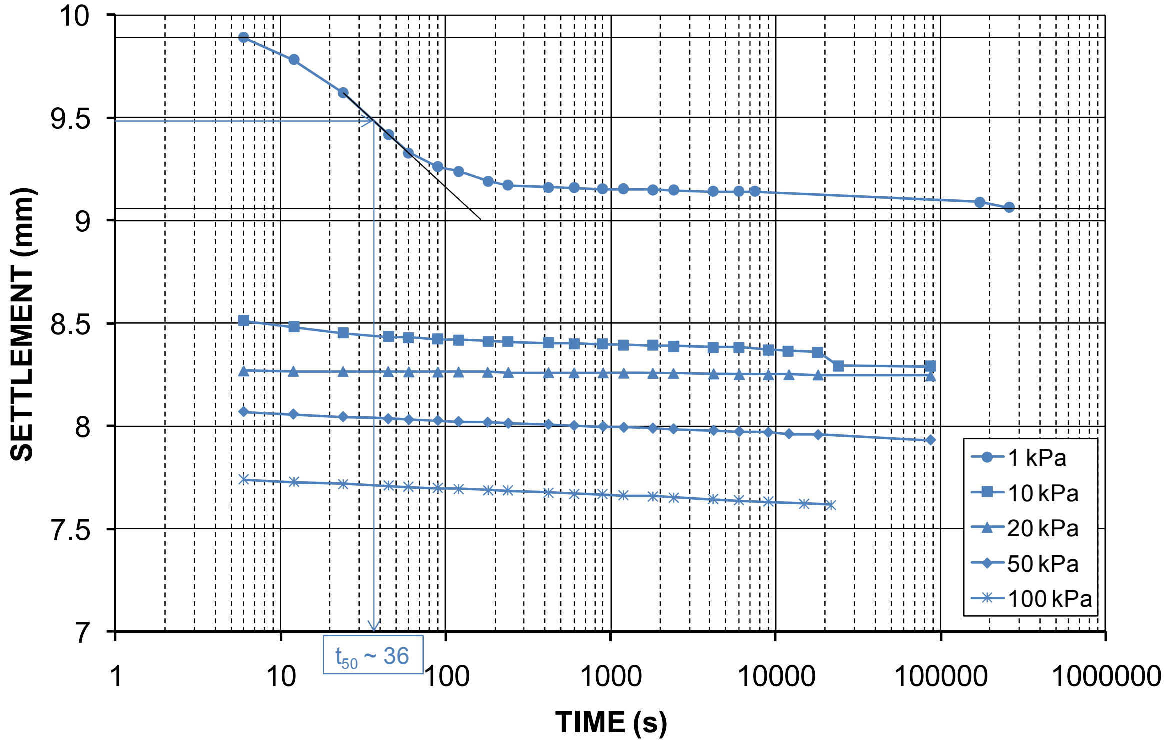

Figure 21 Oedometer settlement vs. Log_{10} (Time) for settled Swanbank fly ash at various effective stresses

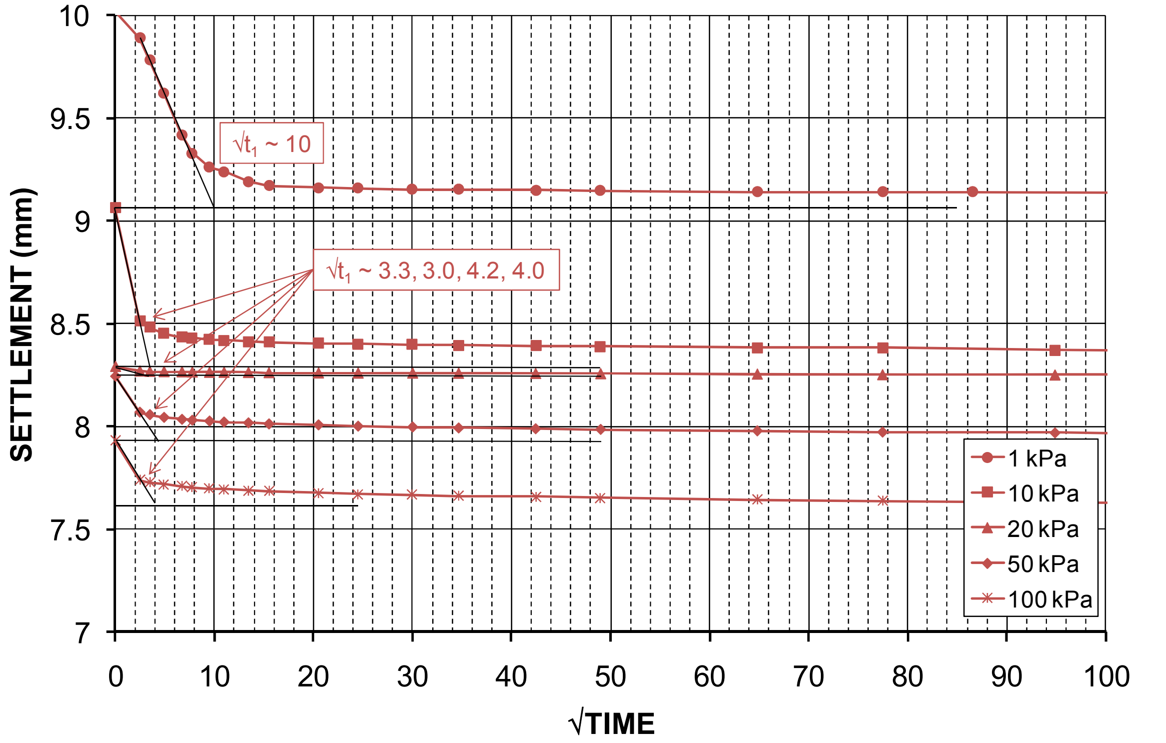

Figure 22 Oedometer settlement vs. √Time for settled Swanbank fly ash at various effective stresses

Table 6 summarises the oedometer test parameters obtained for Swanbank fly ash.

Table 6 Oedometer test parameters

EFFECTIVE STRESS σ_v' (kPa)	VOID RATIO e	COEFFICIENT OF CONSOLIDATION c_v (m^2/year)		COEFFICIENT OF VOLUME DECREASE m_v (m^2/MN)	HYDRAULIC CONDUCTIVITY k (m/s)	
		Log_{10}Time	√Time		Log_{10}Time	√Time
0		-	-	-	-	-
1		3.91	5.64	6.537	7.95 x 10^{-9}	1.15 x 10^{-8}
10		-	42.8	0.665	-	8.85 x 10^{-9}
20		-	47.0	0.333	-	4.87 x 10^{-9}
50		-	45.9	0.134	-	1.91 x 10^{-9}
100		-	23.4	0.068	-	4.91 x 10^{-9}
Averages		**3.91**	**33.0**	**1.547**	**7.95 x 10^{-9}**	**5.52 x 10^{-9}**

The c_v values given in Table 6 may be compared with a typical c_v value of 2.6 m^2/year for Kaolin. Plots of the Coefficients of Consolidation calculated for Swanbank fly ash versus void ratio and effective stress are plotted in Figures 23 and 24, respectively.

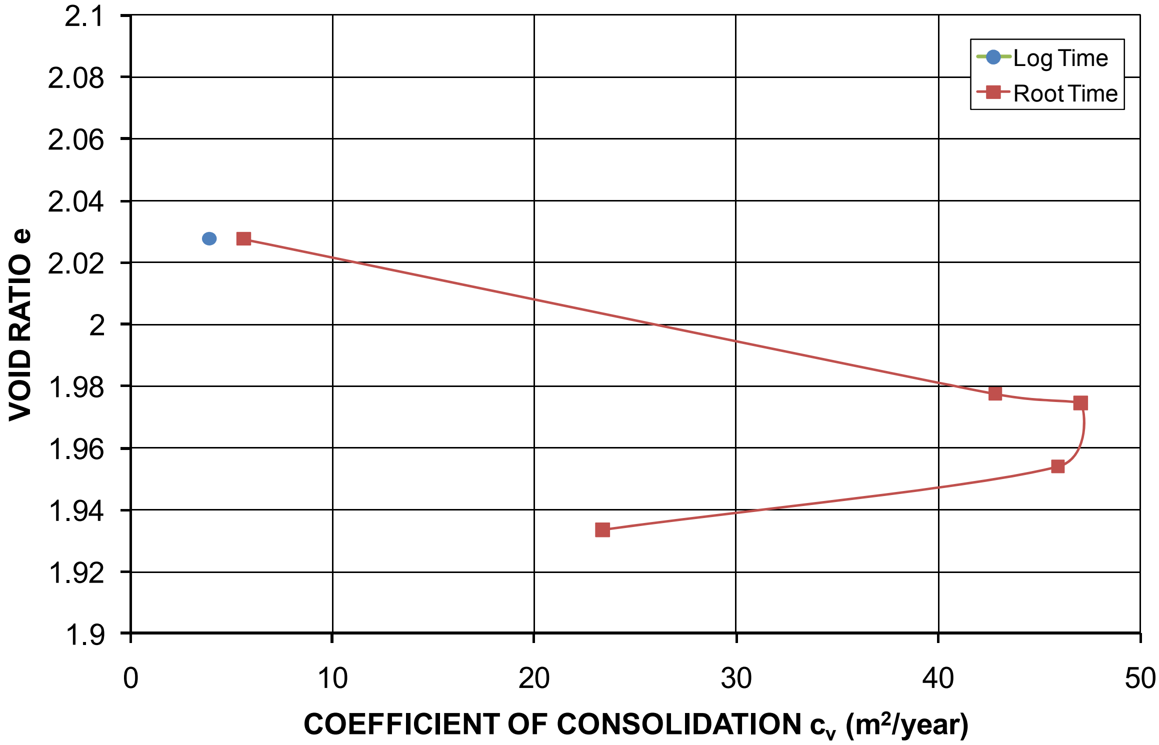

Figure 23 Void ratio vs. Coefficient of Consolidation for Swanbank fly ash

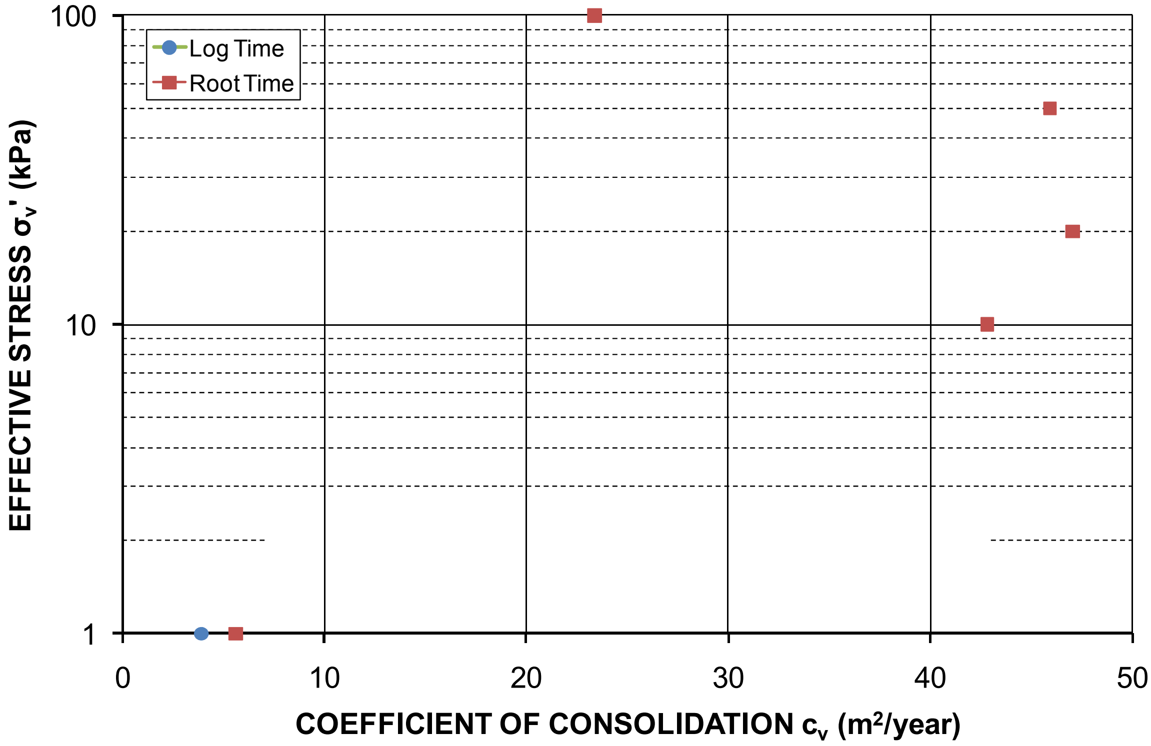

Figure 24 Effective stress vs. Coefficient of Consolidation for settled Swanbank fly ash

The Coefficient of Volume Decrease m_v, which is a measure of the instantaneous slope of the void ratio versus effective stress plot to natural scales, is given by:

$$m_v = 0.435\, C_c/\{(1+e)\, \sigma_v'\} \quad [4]$$

The Hydraulic Conductivity k is then calculated from:

$$k = c_v\, m_v\, \gamma_w \quad [5]$$

The m_v and k values calculated from the Swanbank fly ash oedometer test data are given in Table 6. Typical values of m_v for normally consolidated (soft) clays range from 0.3 to 1.5 m^2/MN; the average m_v value calculated for Swanbank fly ash corresponds to the most compressible end of this range. Plots of the Hydraulic Conductivities calculated for Swanbank fly ash versus void ratio and effective stress are plotted in Figures 25 and 26, respectively, which show well correlated relationships.

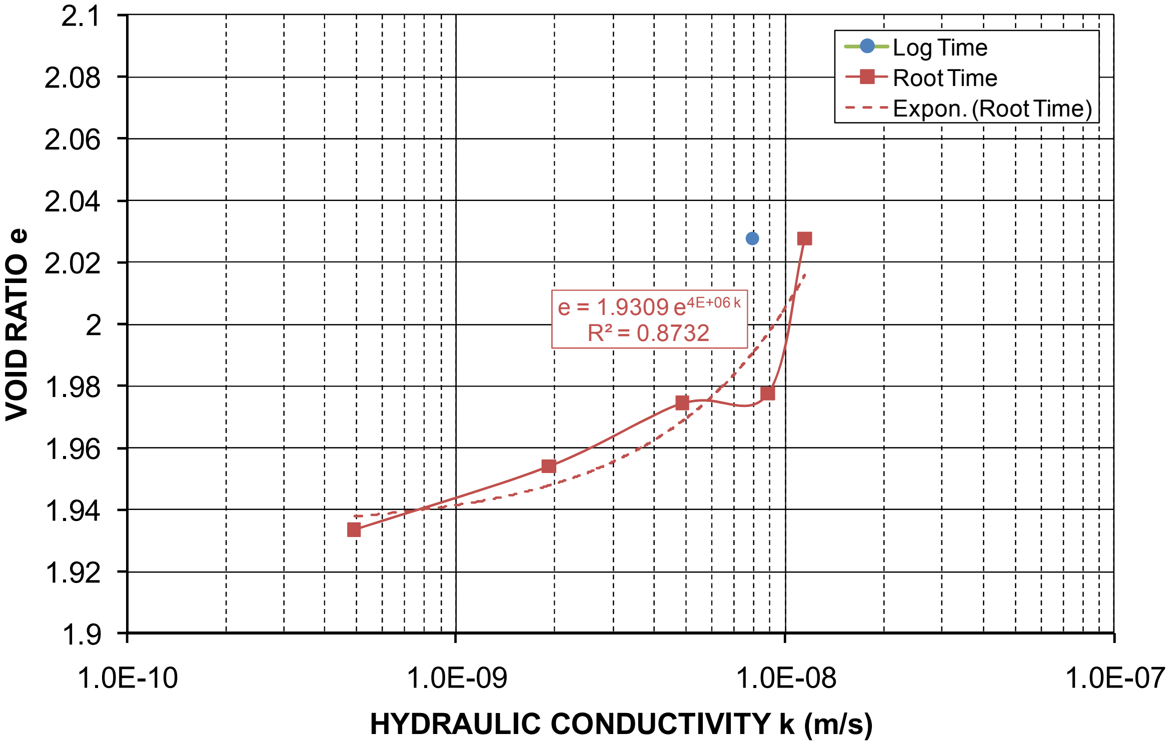

Figure 25 Void ratio vs. Hydraulic conductivity for Swanbank fly ash

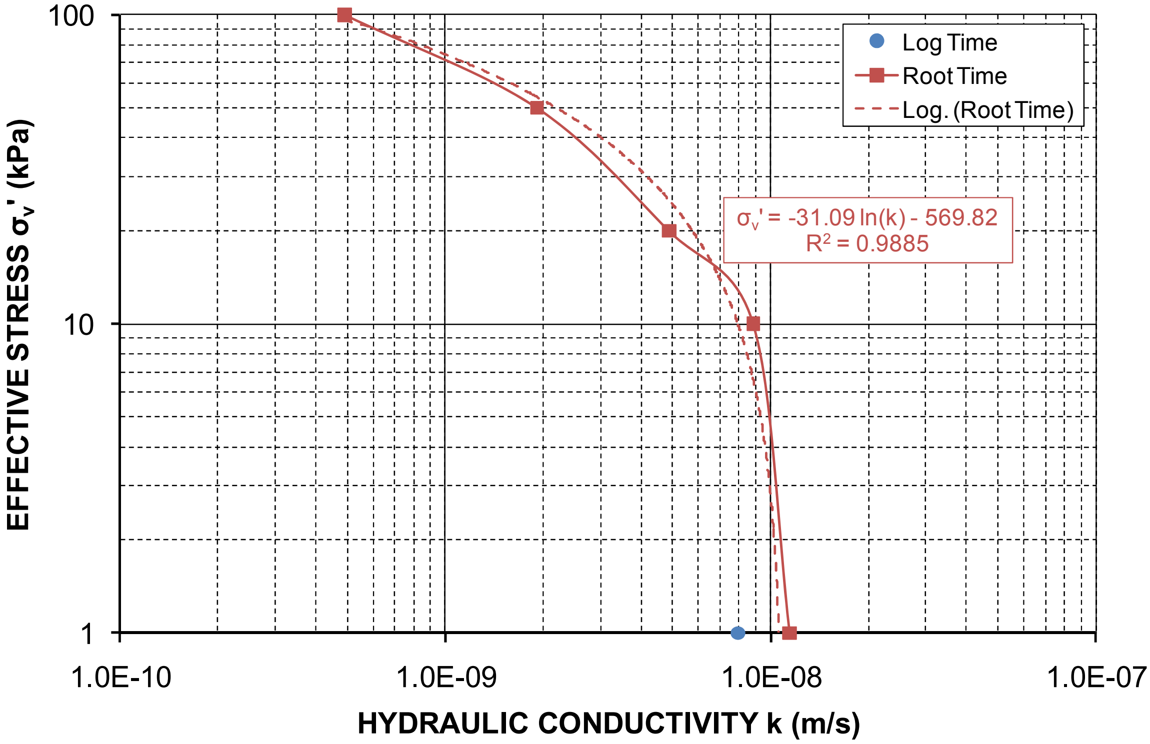

Figure 26 Effective stress vs. Coefficient of consolidation for Swanbank fly ash

4.3 Laboratory Flume Testing of Swanbank Fly Ash

Figure 27 summarises all of the open-ended beach profiles obtained for Swanbank fly ash tested at different % solids in the laboratory flume. Clearly, the higher the initial % solids, the steeper the beach profile, with ≤ 35% solids producing an almost flat beach.

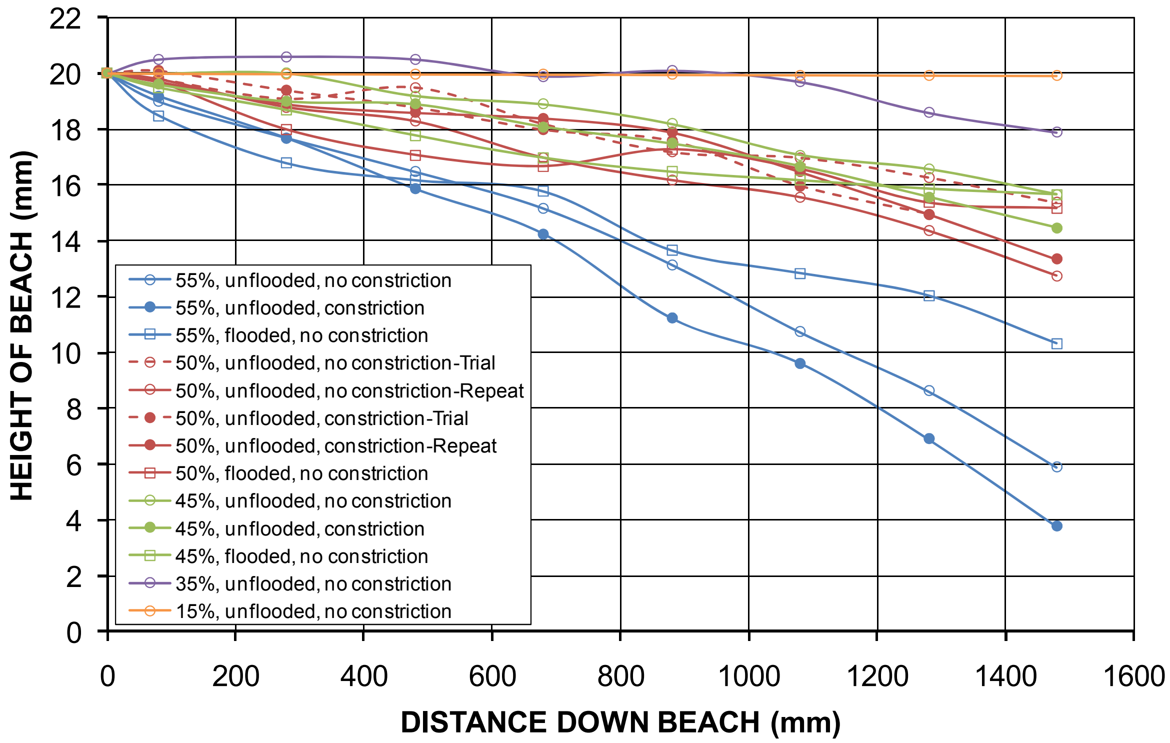

Figure 27 Summary of open-ended laboratory flume beach profiles for Swanbank fly ash

Figures 28, 29 and 30 show the open-ended beach profiles obtained for Swanbank fly ash tested at 55%, 50% and 45% solids, respectively, in the laboratory flume. At 55% solids, the steepest beach slope occurs due to a constriction, and the flattest beach slope occurs due to flooding. At ≤ 50% solids, there is little distinction between beaches regardless of whether they are unflooded, flooded or constricted.

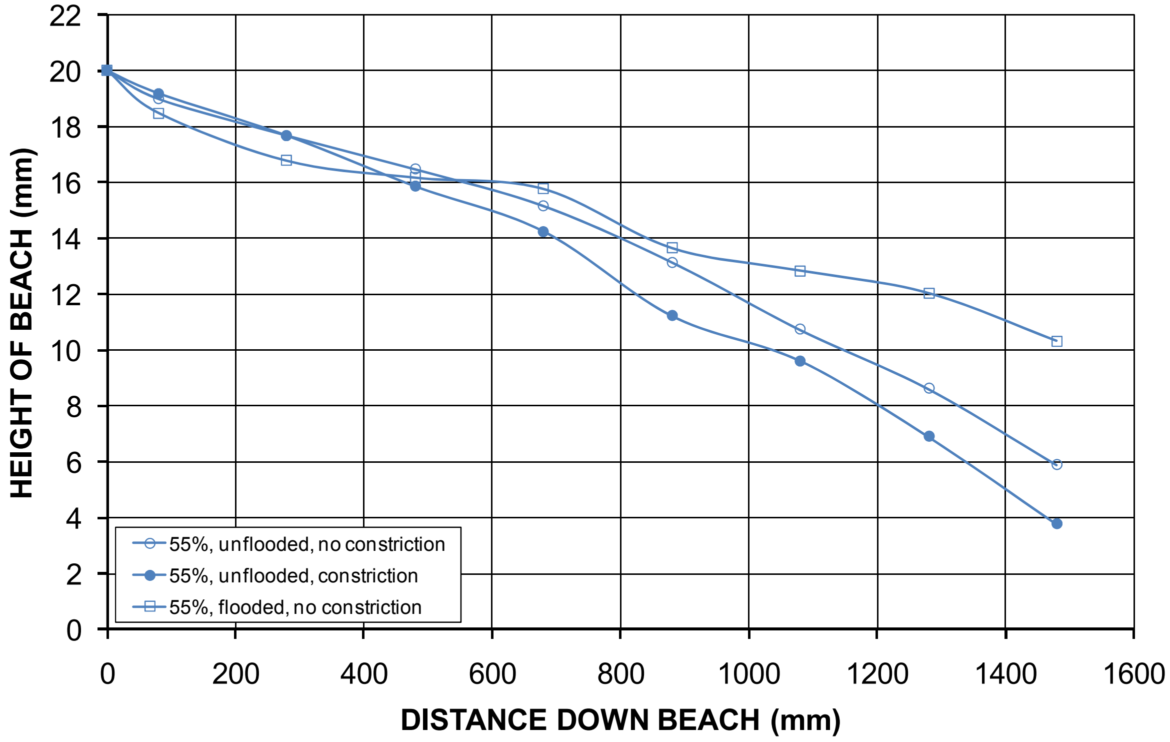

Figure 28 Summary of open-ended laboratory flume beach profiles for Swanbank fly ash

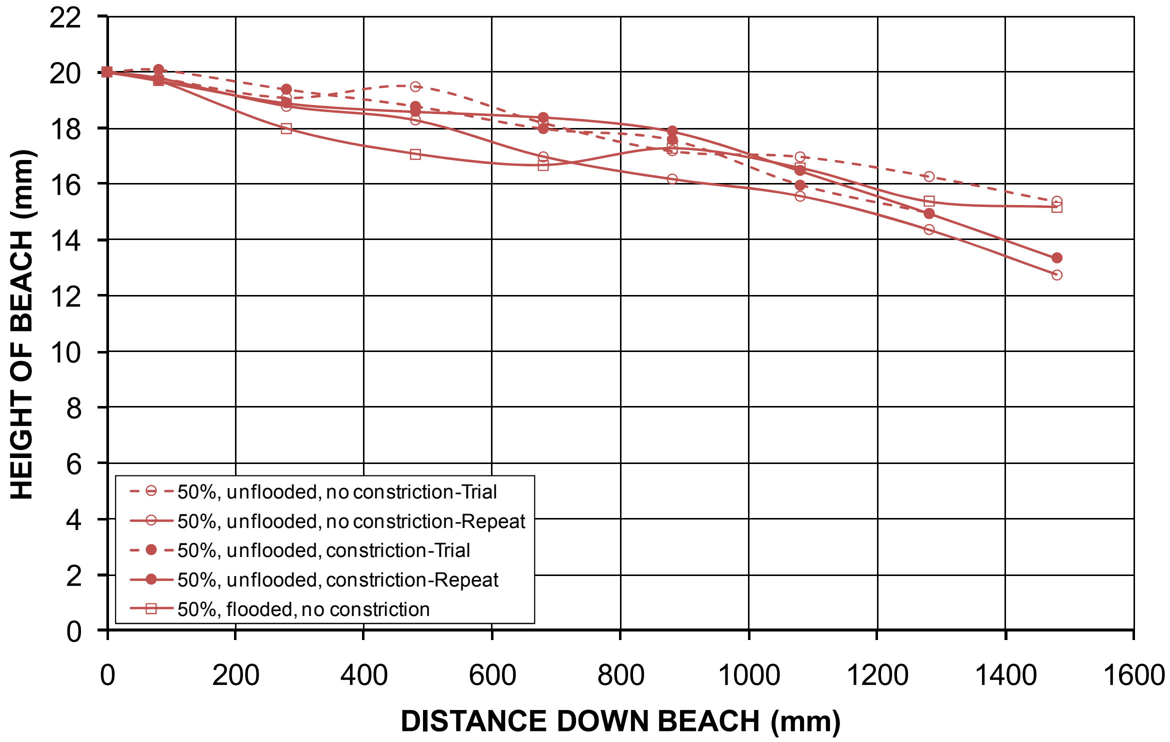

Figure 29 Summary of open-ended laboratory flume beach profiles for Swanbank fly ash

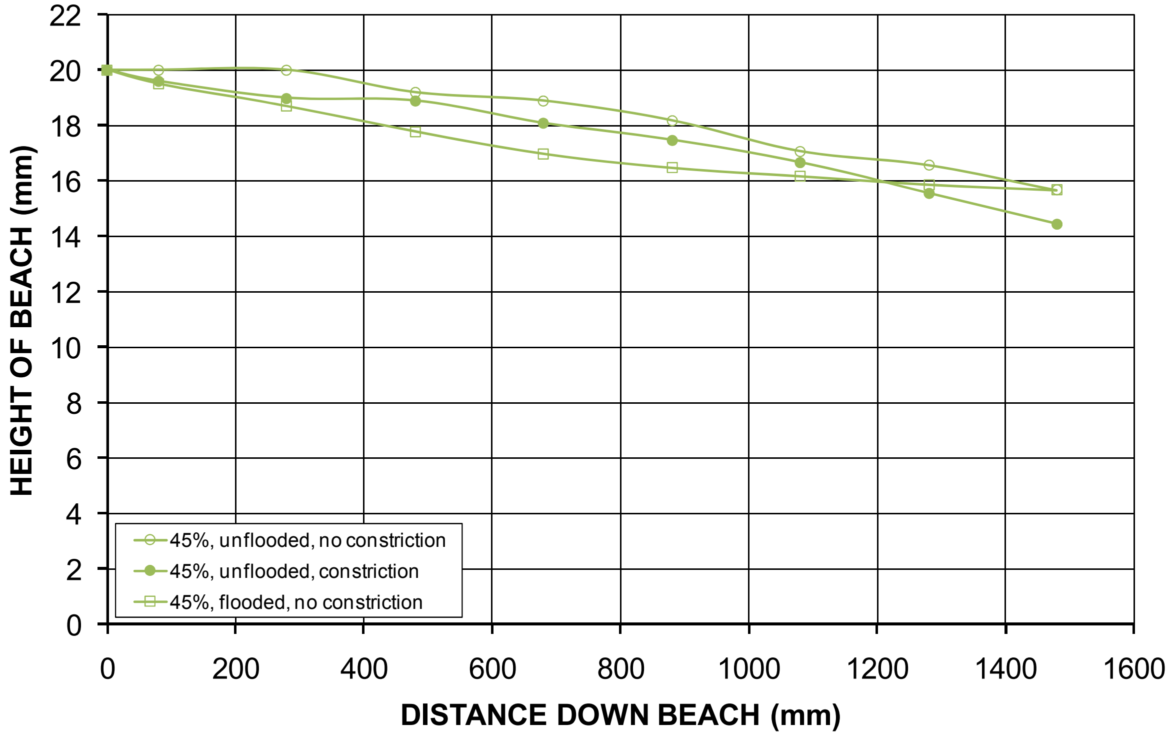

Figure 30 Summary of open-ended laboratory flume beach profiles for Swanbank fly ash

4.3.1 Sub-Aerial, Unconstricted Beaching

Figure 31 compares the open-ended, unflooded, unconstricted beach profiles obtained for Swanbank fly ash tested at different % solids in the laboratory flume, highlighting that the higher the initial % solids the steeper the beach profile.

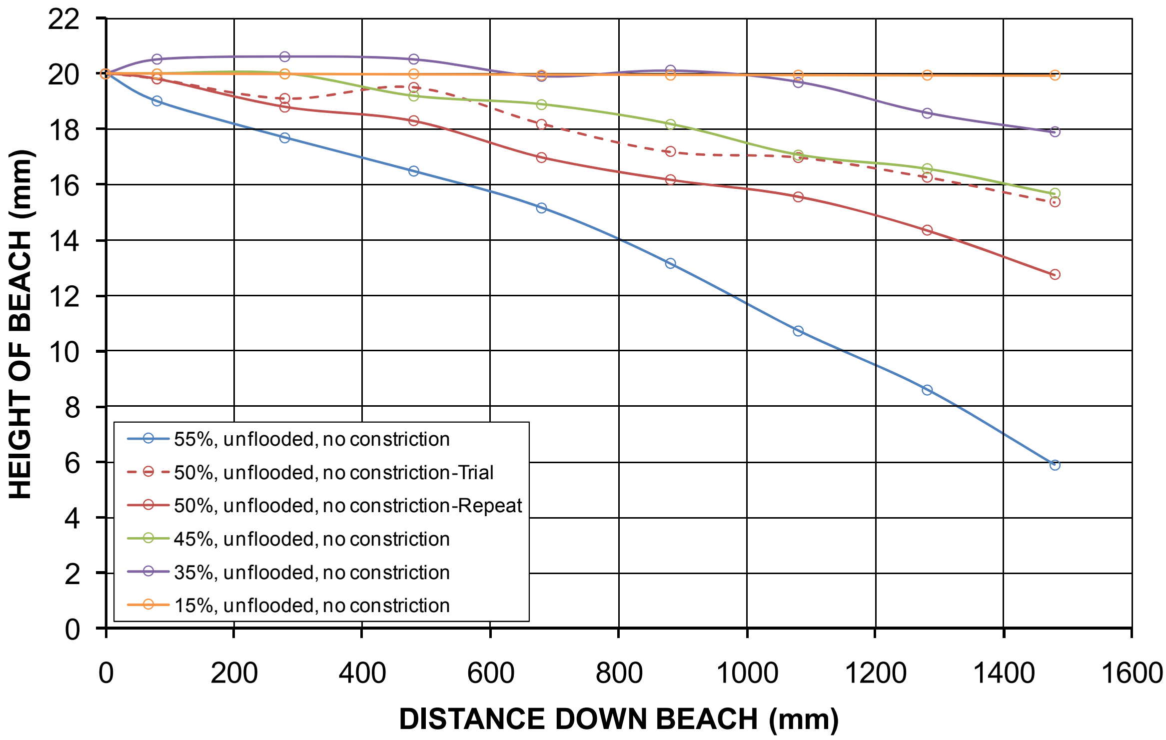

Figure 31 Laboratory flume test beach profiles for unflooded, unconstricted deposition of Swanbank fly ash

4.3.2 Sub-Aerial, Constricted Beaching

Figure 32 compares the open-ended, unflooded, constricted beach profiles obtained for Swanbank fly ash tested at different % solids in the laboratory flume, highlighting that only 55% solids produces a markedly steeper beach profile. The constriction has the effect of holding back the slurry, leading to a reduced beach slope before the constriction, and frees up the slurry flow beyond the constriction, leading to a steeper beach slope.

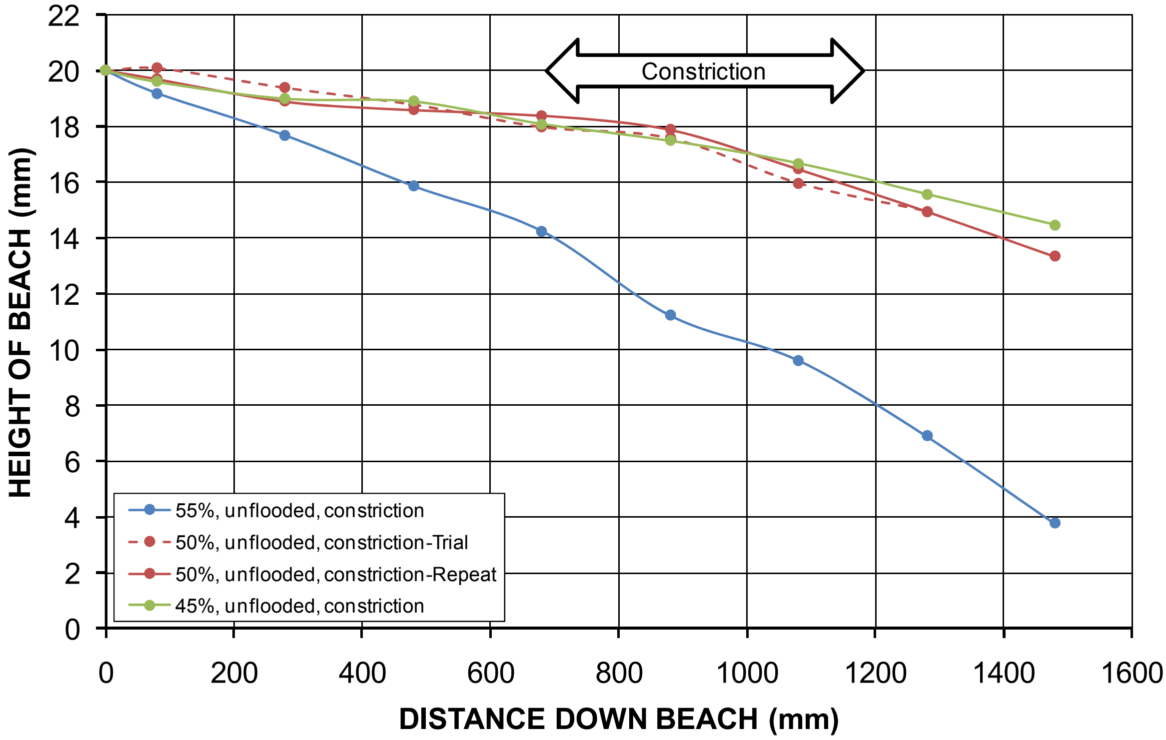

Figure 32 Laboratory flume test beach profiles for unflooded, constricted deposition of Swanbank fly ash

4.3.3 Under Water, Unconstricted Beaching

Figure 33 compares the open-ended, flooded, unconstricted beach profiles obtained for Swanbank fly ash tested at different % solids in the laboratory flume, highlighting that only 55% solids produces a markedly steeper beach profile.

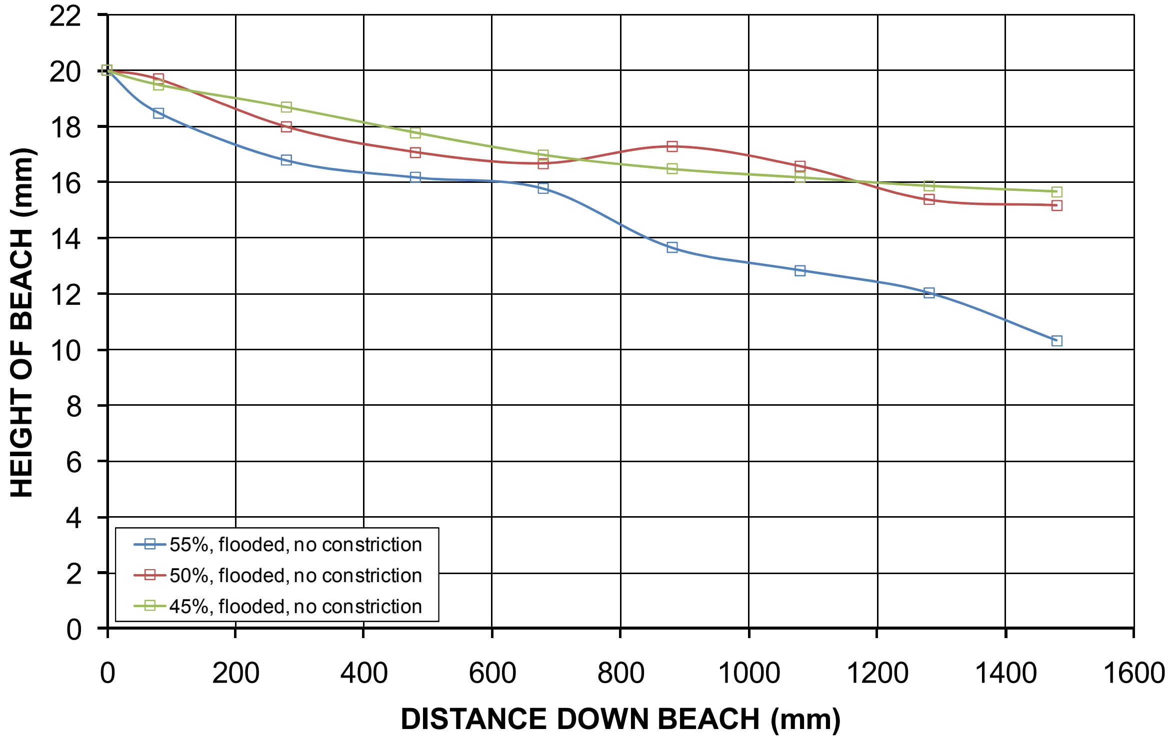

Figure 33 Laboratory flume test beach profiles for flooded, unconstricted deposition of Swanbank fly ash

4.3.4 Constricted Backfilling, Under Water and a Head of Slurry

Figure 34 shows the settled slurry profile resulting from flooded deposition of Swanbank slurry initially at 55% solids, under a low slurry head into a closed-ended constriction.

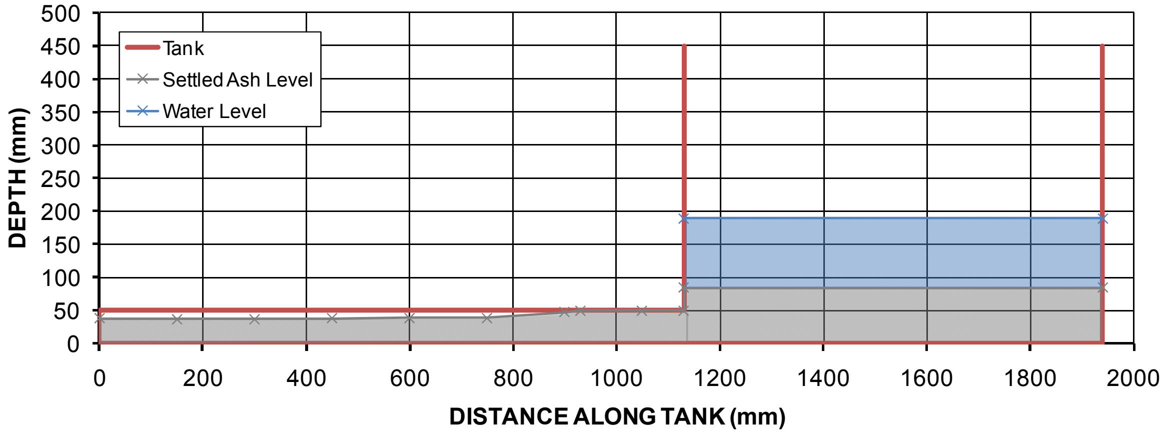

Figure 34 Constricted backfilling, under water and a low head of Swanbank fly ash slurry, initially at 50% solids

Figure 35 shows the settled slurry profile resulting from flooded deposition of Swanbank slurry initially at 55% solids, under a high slurry head into a closed-ended constriction.

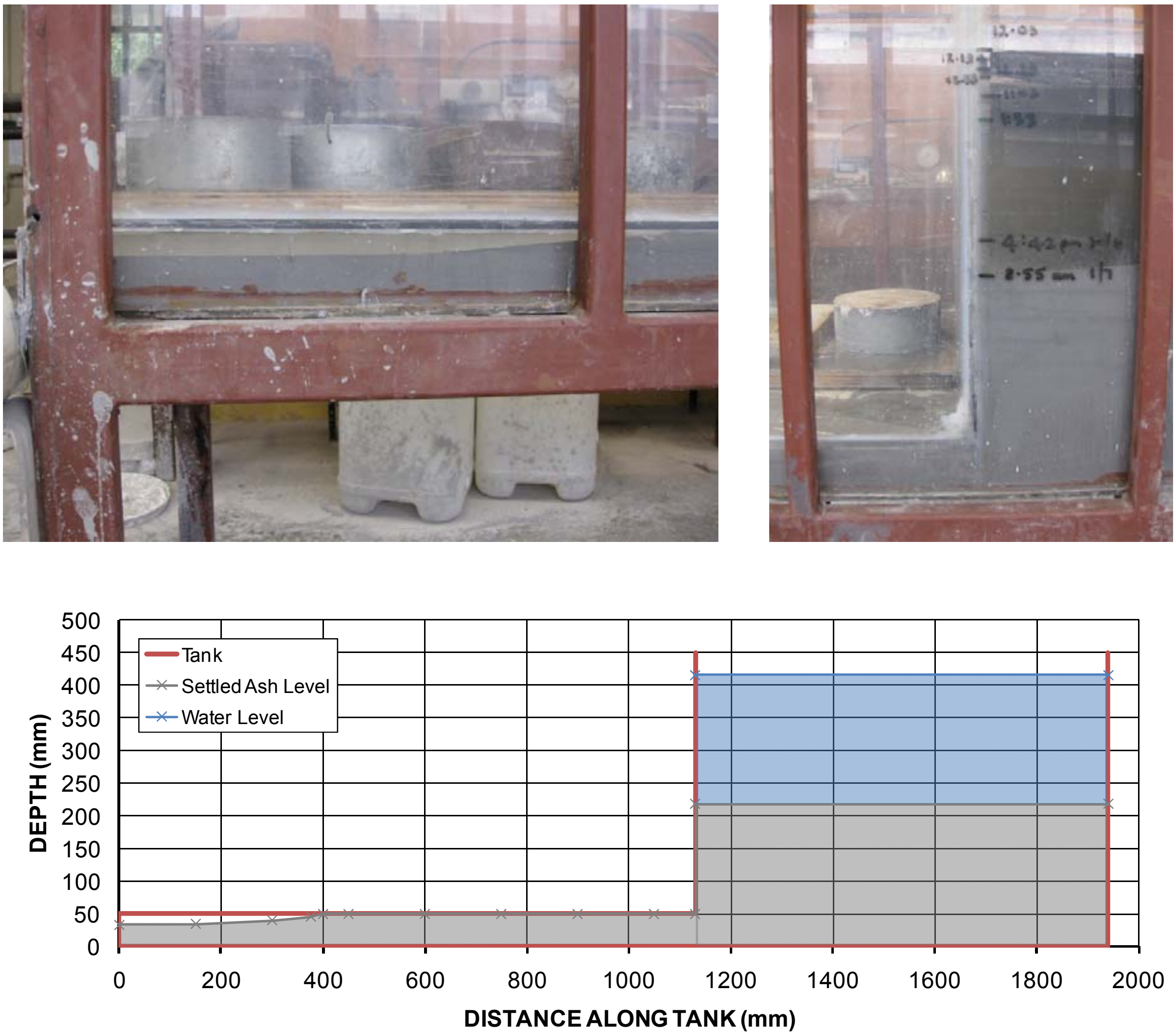

Figure 35 Constricted backfilling, under water and a high head of Swanbank fly ash slurry, initially at 50% solids

Figure 36 shows the settled slurry profile resulting from flooded deposition of Swanbank slurry initially at 60% solids, under a high slurry head into a closed-ended constriction.

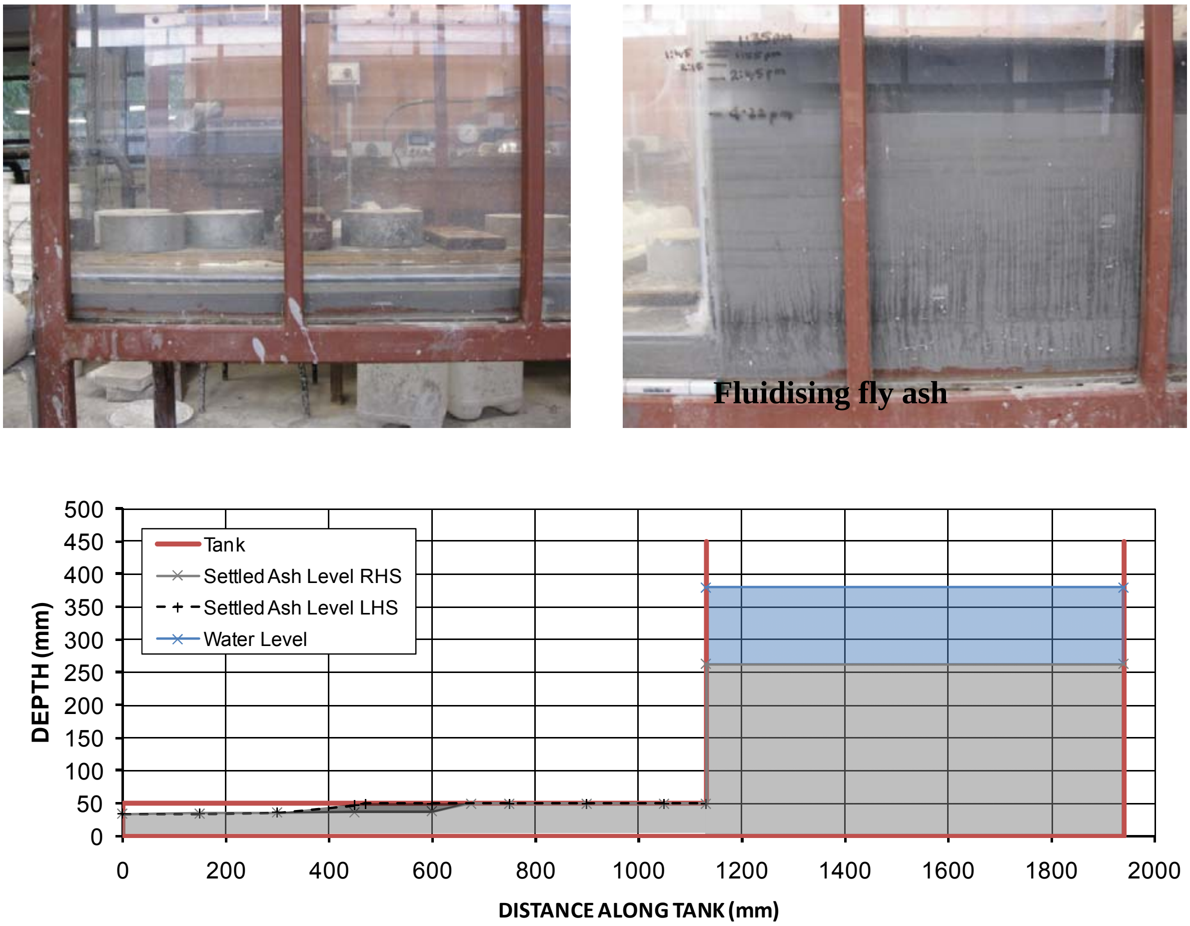

Figure 36 Constricted backfilling, under water and a high head of Swanbank fly ash slurry, initially at 60% solids

The results of the constricted backfilling flume tests under water and a head of slurry are summarised in Tables 7 and 8, and Figures 37 to 39, which highlight the dramatic effect of applying a head of slurry in increasing the final % solids and dry density (from about 1.0 g/cm^3 without an applied head to about 1.5 g/cm^3 with an applied head), and driving the filling (through fluidisation) of the constriction following initial settling within it. Applying a high head of slurry appears more effective in driving backfilling than a higher initial % solids. Table 8 suggests that the reason for this is the lower final hydraulic gradient for 50% solids (of about 0.28, compared with 0.44 for 60% solids).

Table 7 Initial and final average % solids, total moisture content and dry density on column settling, and on flume testing under a head of Swanbank fly ash slurry

% SOLIDS		TOTAL MOISTURE CONTENT (%)		DRY DENSITY (g/cm^3)	
Initial	Final	Initial	Final	Initial	Final
On column settling (no excess head of fly ash slurry)					
55	64.9	45	35.1	0.771	0.980
50	66.7	50	33.3	0.676	1.022
45	68.0	55	32.0	0.588	1.053
35	72.2	65	27.8	0.428	1.157
Flume testing 50 mm void under high head of slurry @ 50% solids (initially 416 mm, finally 218 mm)					
50	88.4	50	11.6	0.676	1.641
Flume testing 50 mm void under high head of slurry @ 60% solids (initially 380 mm, finally 263 mm)					
60	82.1	40	17.9	0.873	1.436

Table 8 Backfilling of constriction on flume testing under a head of Swanbank fly ash slurry

HEAD OF SLURRY (mm)		FINAL LENGTH FILLED (mm)	FINAL HEAD OF SLURRY/LENGTH BACKFILLED
Initial	Final		
Flume testing 50 mm void under low head of slurry @ 50% solids			
189	84	300	0.28
Flume testing 50 mm void under high head of slurry @ 55% solids			
416	218	800	0.27
Flume testing 50 mm void under high head of slurry @ 60% solids			
380	263	600	0.44

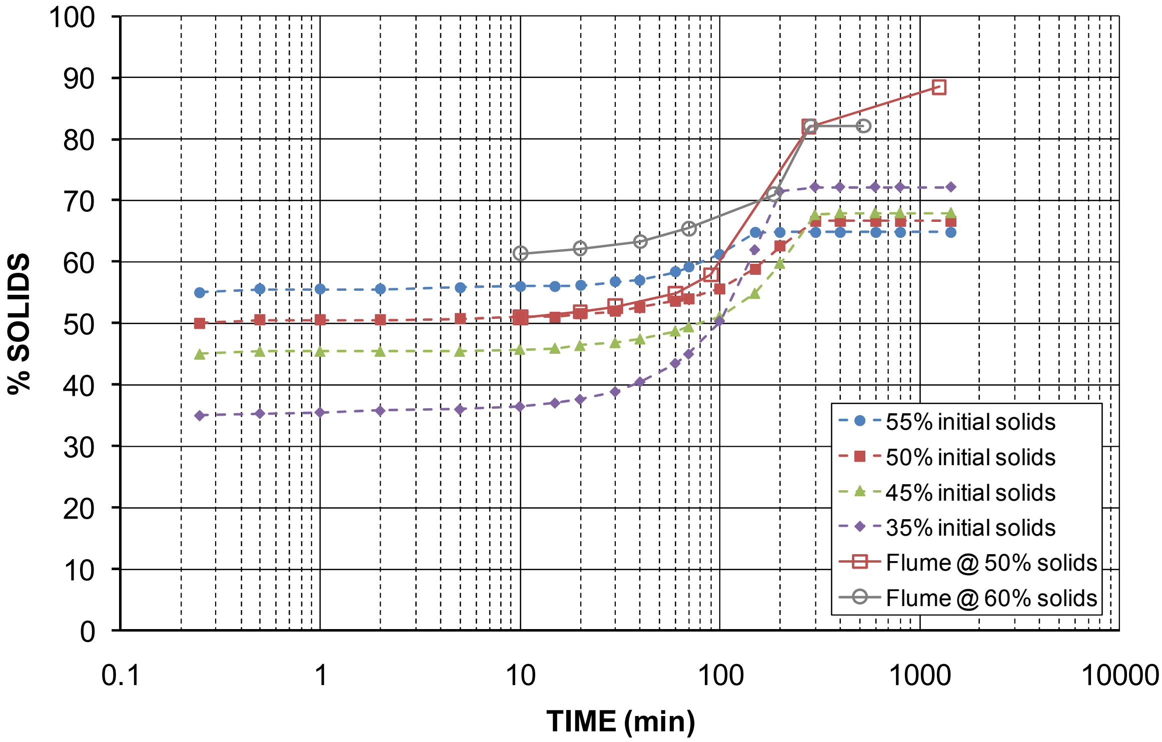

Figure 37 Comparison of Swanbank fly ash average % solids on settling column, and flume testing under water and under a high head

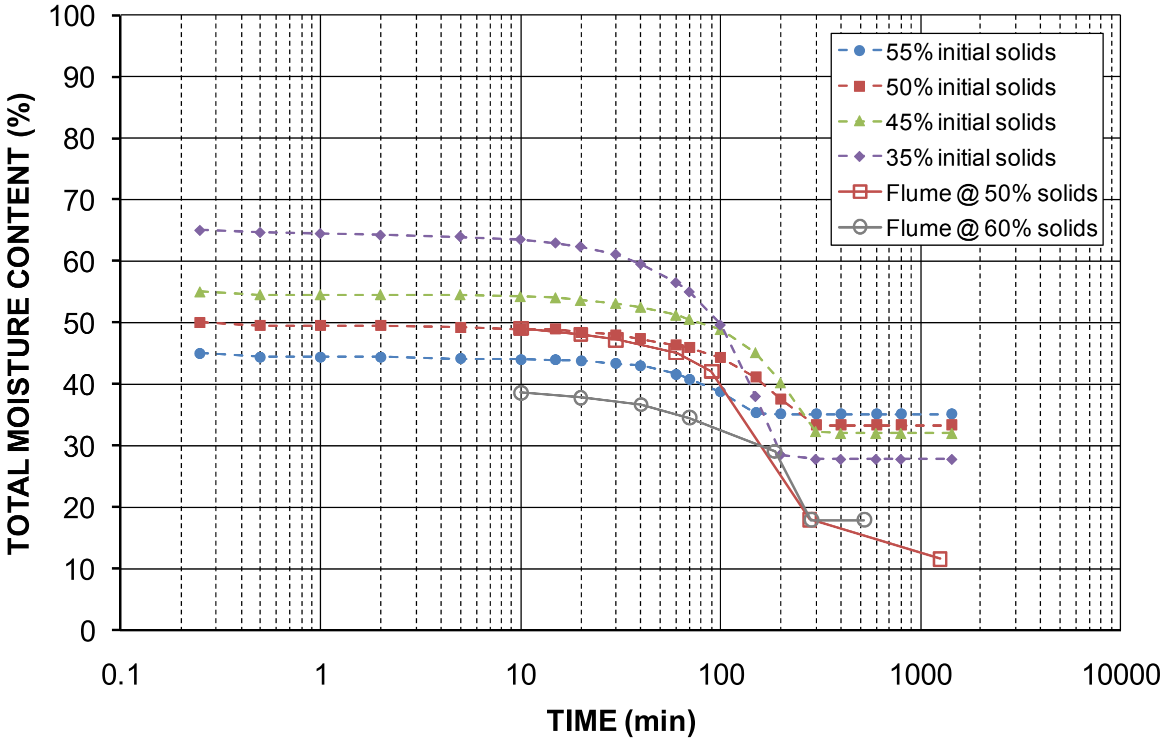

Figure 38 Comparison of Swanbank fly ash average total moisture contents on settling column, and flume testing under water and under a high head

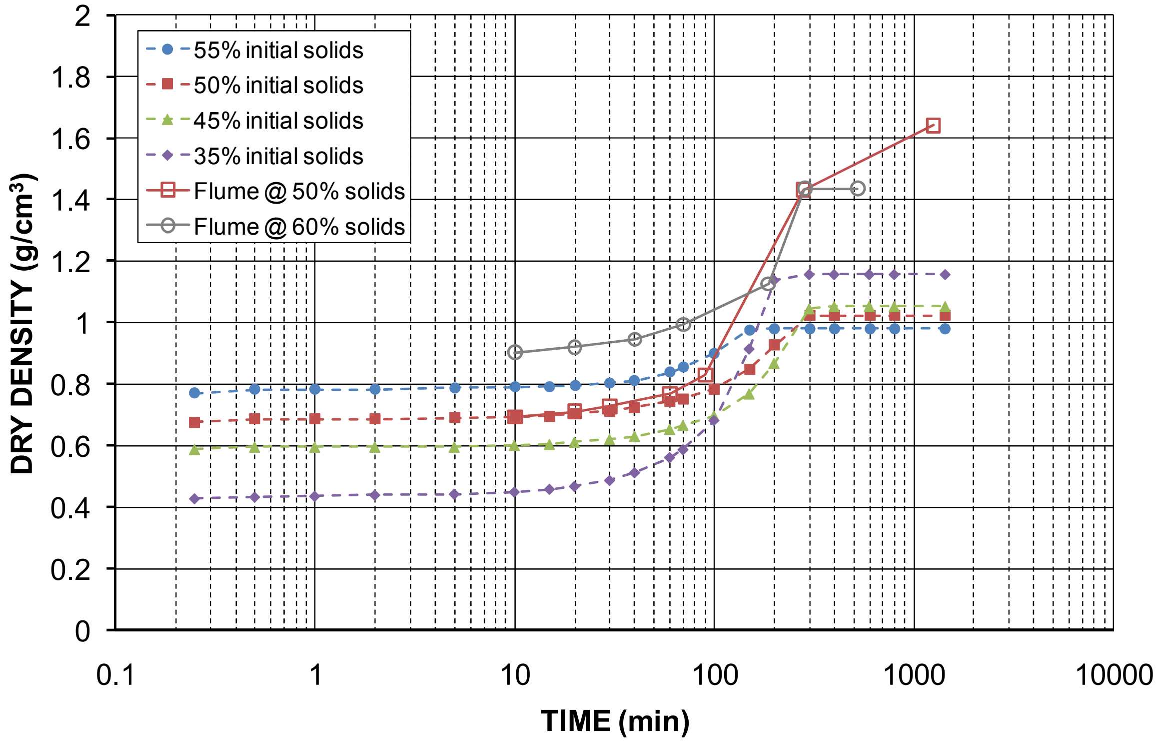

Figure 39 Comparison of Swanbank fly ash average dry density on settling column, and flume testing under water and under a high head

4.4 Field Beach at Swanbank

Figure 40 shows the field beach profile for Swanbank fly ash, and Figure 41 compares the non-dimensional field and laboratory beach profiles, the latter showing that the non-dimensional field profile is in reasonable agreement with the corresponding laboratory profile for an initial % solids of 15%.

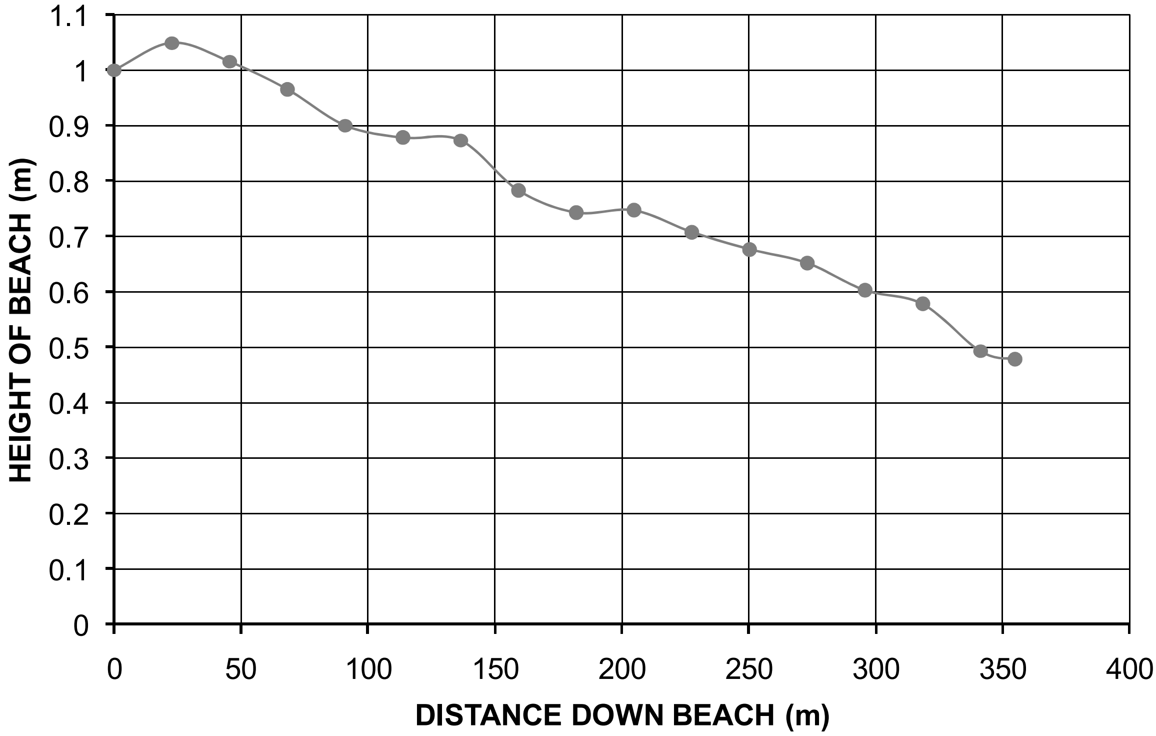

Figure 40 Field beach profile for sub-aerial, unconstricted deposition of Swanbank fly ash

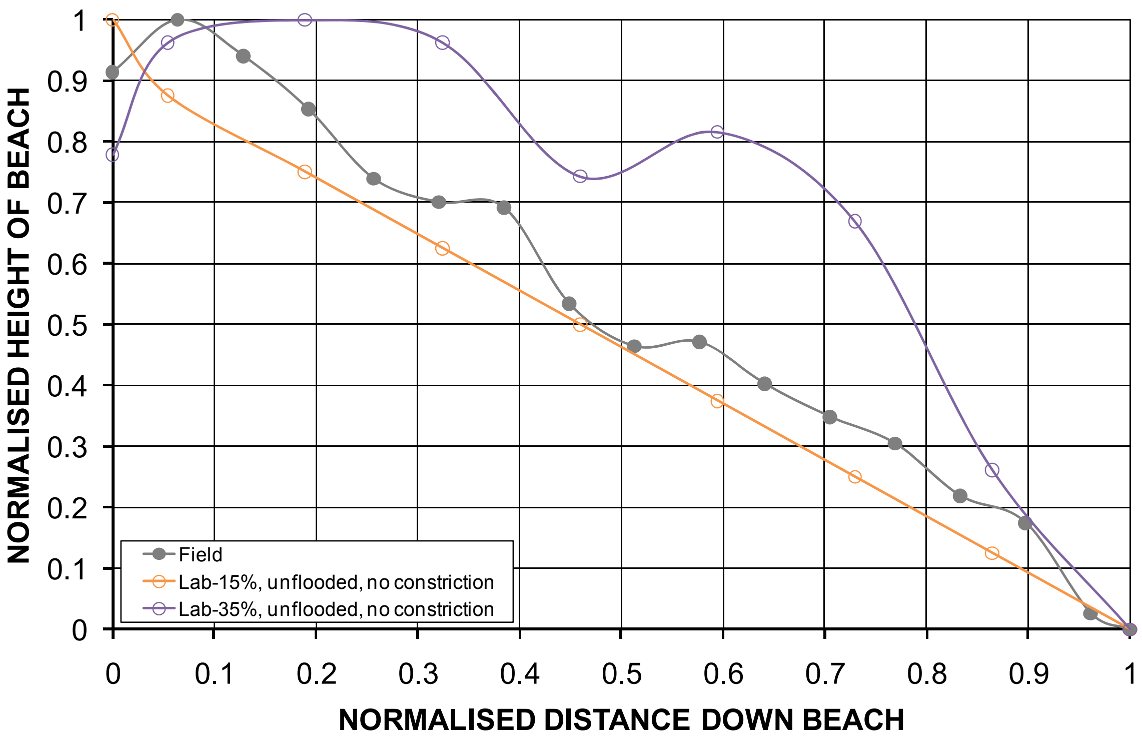

Figure 41 Comparison of non-dimensional field and laboratory beach profiles for sub-aerial, unconstricted deposition of Swanbank fly ash

Figure 42 shows the particle size distribution curves obtained for samples taken along the field beach, Figure 43 shows the decrease in median particle size down the beach, and Figures 44 and 45 show, respectively, the increase in total moisture content and corresponding increase in % solids down the beach. The linear fits to the data in Figures 43 to 45 are relatively poor, but indicate trendlines.

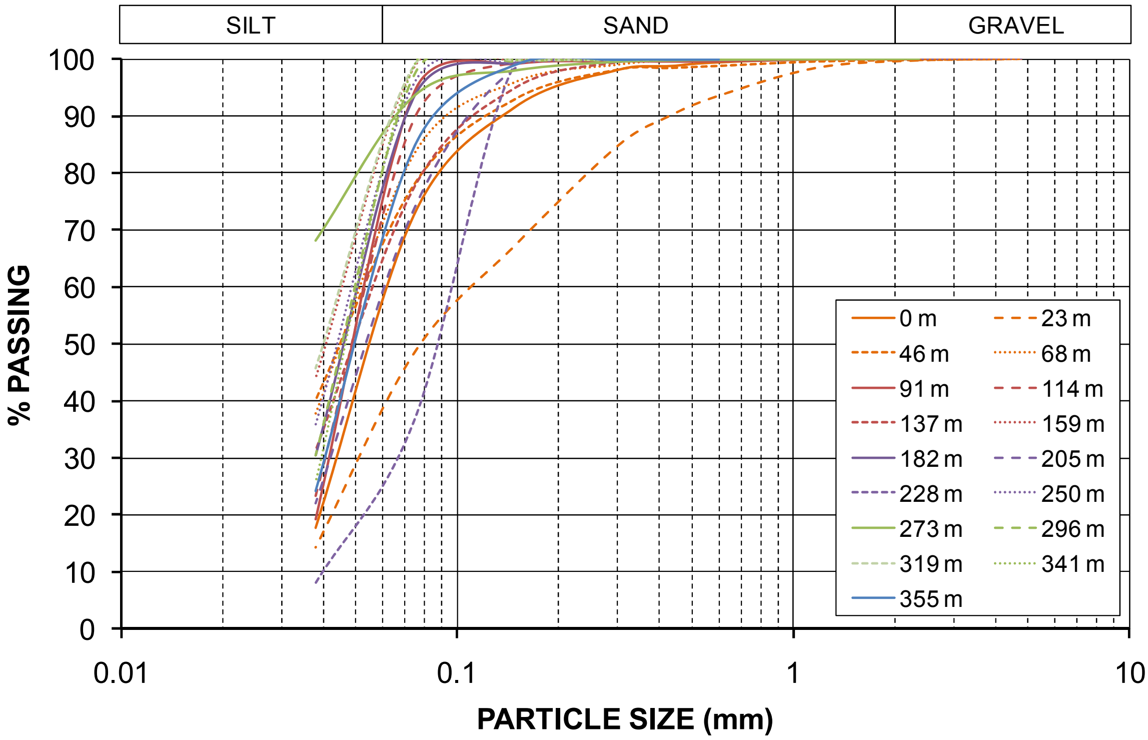

Figure 42 Particle size distribution curves down field beach profile for sub-aerial, unconstricted deposition of Swanbank fly ash

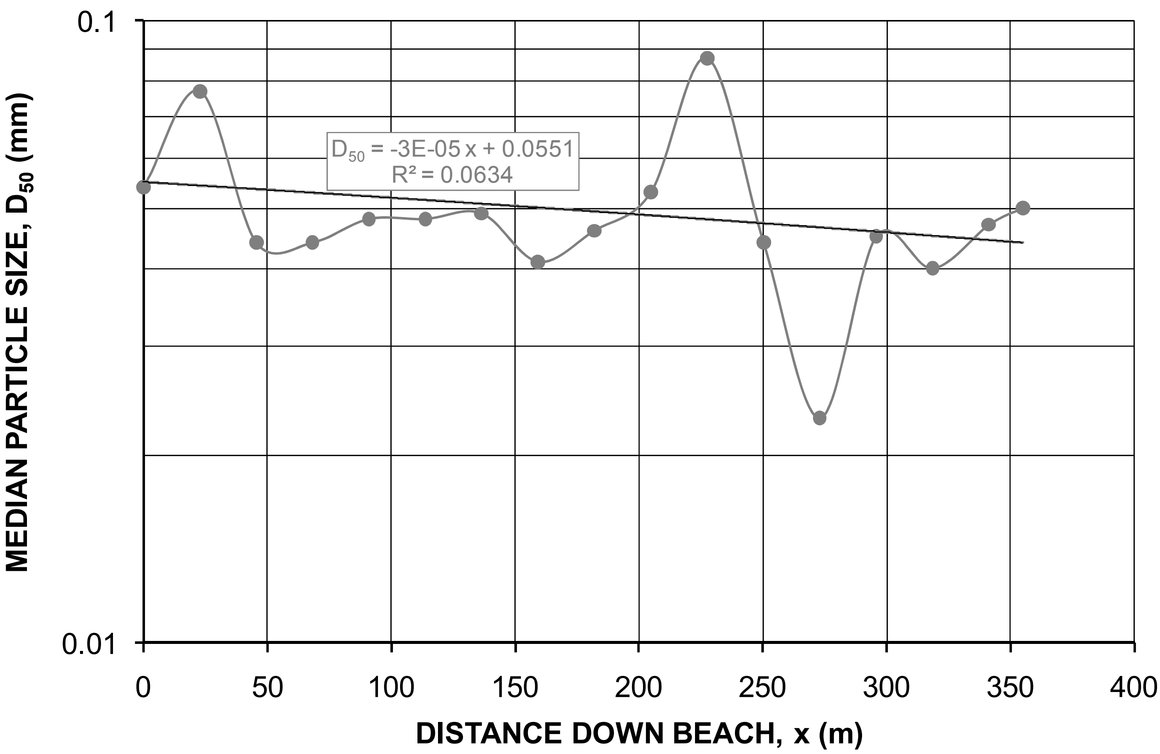

Figure 43 Median particle size down field beach profile for sub-aerial, unconstricted deposition of Swanbank fly ash

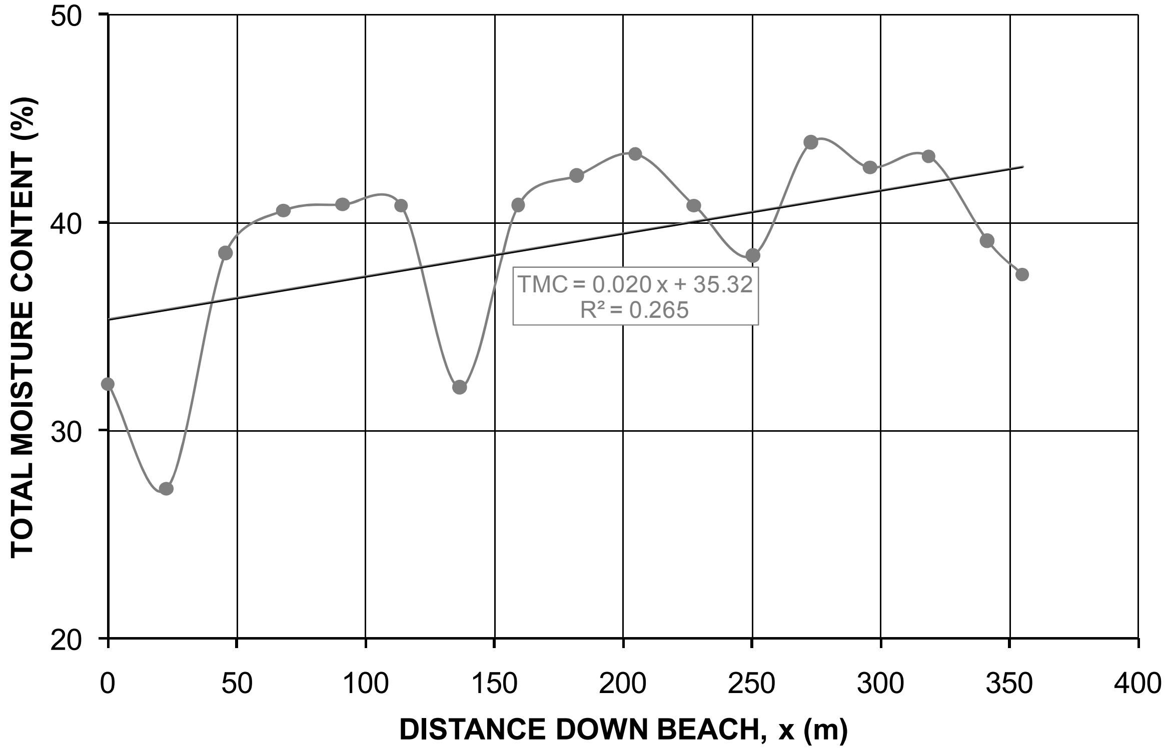

Figure 44 Total moisture content down field beach profile for sub-aerial, unconstricted deposition of Swanbank fly ash

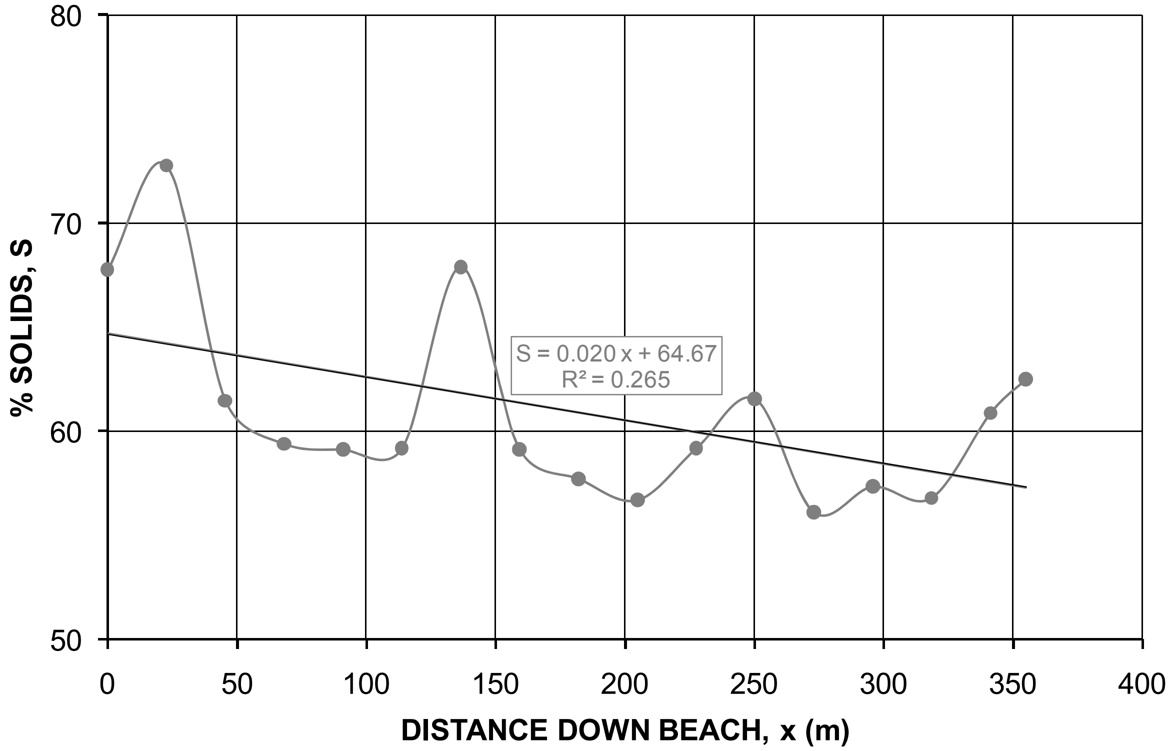

Figure 45 % Solids down field beach profile for sub-aerial, unconstricted deposition of Swanbank fly ash

4.5 Comparison of Average Laboratory and Field Beach Slopes

Figure 46 compares the average laboratory and field beach slopes obtained for Swanbank fly ash at different initial % solids, which highlights that for unflooded, unconstricted beaching the average beach slope is highest (at about 1%) for an initial % solids of 55%, lower but insensitive over the intermediate range of initial % solids, and flat for an initial % solids of 15%. The average field beach slope of 0.014% is similar to that obtained in the laboratory for an initial % solids of 15% (similar to the field initial % solids), and the non-dimensional beach profile is similar to that for the field profile.

For unflooded, constricted beaching the average beach slope is significantly greater at high initial % solids, and only slightly greater at intermediate initial % solids. Flooding generally has little effect on the average beach slope for unconstricted beaching.

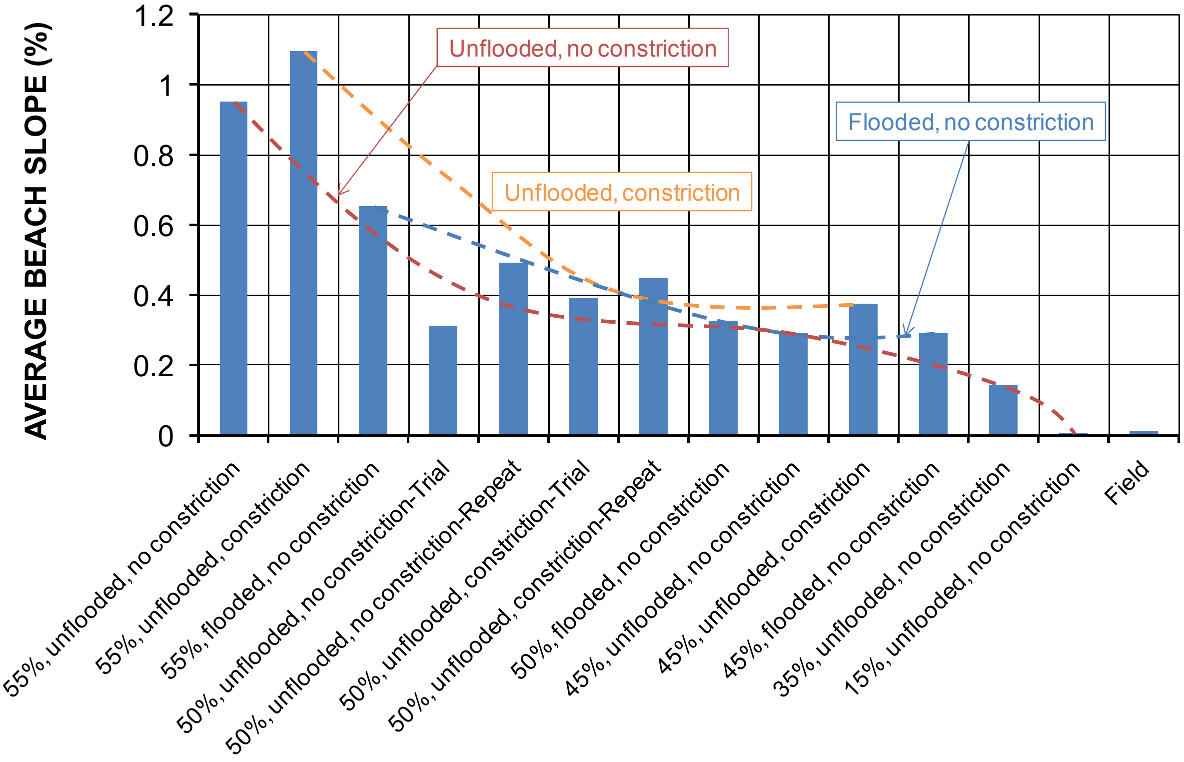

Figure 46 Comparison of average beach slopes of laboratory and field beach profiles for Swanbank fly ash

5 IMPLICATIONS FOR FULL-SCALE BACKFILLING

The open-ended laboratory flume testing has shown that the upper limit for the Swanbank fly ash to flow (without the application of an extra head of slurry) is about 55% solids, which may correspond to from 50 to 60% solids at field scale, depending on the applied head of fly ash. Laboratory flume testing at an initial % solids of 55% results in an average unconstricted laboratory beach slope of about 1% if unflooded, and about 0.6% if flooded. Lower initial % solids result in flatter beaches. The field fly ash beach (unflooded and unconstricted, but at much lower % solids) has an average slope of only 0.014%. Since higher initial % solids result in steeper beach profiles, underground voids would not fill as well, unless blocked off, although the solids would settle less, leading to less residual void space. The poor filling of underground voids could be overcome to some extent by progressive filling, provided that the void slopes away from the delivery point.

At 50 to 60% solids, Swanbank fly ash deposited under an applied head of slurry will fill the void created by a closed-ended constriction, representing a blocked-off bord and pillar roadway and openings with fly ash slurry delivered via a borehole. It appears that complete filling of such a roadway is more effective for fly ash slurry at an initial % solids of 50% rather than 60%, since at the lower initial % solids the fly ash more readily fluidises, which facilitates filling of the void left as the fly ash solids settle, and a gain in dry density from about 1 g/cm^3 with no applied head to about 1.5 g/cm^3 with an applied head of slurry. Again, the void should slope away from the delivery point to facilitate filling through fluidisation.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

To facilitate the backfilling and support of bord and pillar roadways and openings with fly ash slurry to provide some support, the following guidelines are suggested:

1. Voids should first be blocked off downslope of the delivery point for the fly ash slurry, to contain the slurry.
2. The optimum initial % solids for the fly ash slurry appears to be in the range from 50 to 60%, to limit the average beach slope and hence maximise initial filling, to make the slurry more capable of fluidising to facilitate void filling following settling, and to increase the final dry density, strength and stiffness achieved. The actual optimal initial % solids will increase with the applied head of fly ash.
3. A head of slurry should be applied in the borehole used to deliver the fly ash slurry, which will facilitate void filling and gain in dry density, strength and stiffness.

6.2 Recommendations for Further Trials

The literature review provided is not exhaustive and does not draw on experience gained in backfilling underground mining voids beneath recent road works in the area. The current testing program has not extended to field-scale testing, and has not explored the pozzollanic potential of Swanbank fly ash, nor the effectiveness of cement addition to the fly ash. These issues warrant further work.