Harnessing the Potential of Geotextile Tubes to Bulk Treat and Dewater Fly Ash Tailings in South Africa

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Abstract

South Africa is host to several coal-fired power stations whose core function is to generate and supply electricity (Department of Environmental Affairs, 2018). As these facilities continue to expand and supply the majority of South Africa with energy and electricity, an expected by-product called fly ash tailings is formed (Päivi Kinnunen, 2022). This pulverized coal-fired boiler ash is stored in large, engineered facilities called 'ash dump facilities' and is generally designed to accommodate the increasing challenges of storing tailings ash. Whilst evidence of successfully operational ash dump facilities exists in South Africa, the utilization rate of tailings ash in South Africa is internationally unnoticeable, thereby paving the way for innovative development in bulk-treating fly ash for use in general construction practices.

Keywords: *'Tailings fly ash', 'Geotextile Tubes', 'Dewatering cells', 'Bulk treating fly ash', 'Geosynthetics'.*

1 Introduction

Research studies on fly ash geopolymers showcase the potential of reusing fly ash tailings (Department of Environmental Affairs, 2018). However, in almost all cases, fly ash is required to be treated for reuse (Gustafson, 2012). Expanding on promoting the utilization of fly ash, this paper focuses on bulk-treating pulverized fly ash using Geotextile Tube dewatering cells. Through this process, fly ash tailings are chemically treated and stored in Geotextile Tubes which serve as bulk dewatering and containment units.

Understanding the molecular structure of fly ash slurries provides a baseline for determining the geotextile requirements. Scanning Electronic Microscopy (SEM) imaging of fly ash slurries is used to determine the chemical composition of fly ash tailings, which indicates the type of geotextile used for dewatering and filtration. SEM imaging is also used to explore the geotextile filament type, which is a significant contributor to its dewatering and filtration efficiencies. The mechanical and physical-chemical properties of fly ash slurries and geotextiles are pertinent requirements for the design and analysis of Geotextile Tube Dewatering Cells.

2 South Africa's potential for bulk treating fly ash tailings

A Geotextile Tube dewatering system is being proposed to South African mining houses, with the expectation of increasing the utilization rate of fly ash tailings, thereby promoting sustainability. South Africa's bulk energy and electricity supplier, Eskom, reports having used 122.7 million Metric tonnes of coal in 2010, which produced 34.16 million Metric tonnes of fly ash (Plessis PWD, 2013). While there are industries that benefit from the production of fly ash tailings, an example being ash brick manufacturers, there is major potential for utilizing fly ash in a wider scope of construction projects, such as geopolymer stabilized road construction layers (Plessis PWD, 2013).

Figure 1 is a schematic diagram illustrating the movement of sludge through hydraulic pumps with a chemically treated admixture (Officine Maccaferri, 2017). The treated slurry is pumped into the Geotextile Tube and laid over a dewatering pad with drainage channels used to channel discharged effluents into collection ponds (Environmental Impact Management Services, 2018). The potential gain of implementing drainage channels is the reuse of the discharged effluent with an initial required water volume of approximately 102.48 litres per 34.16 metric tonnes of solids (Plessis PWD, 2013). Once the initial water requirement is supplied, the system can become more sustainable, with the proposal of repeatedly reusing expelled effluent.

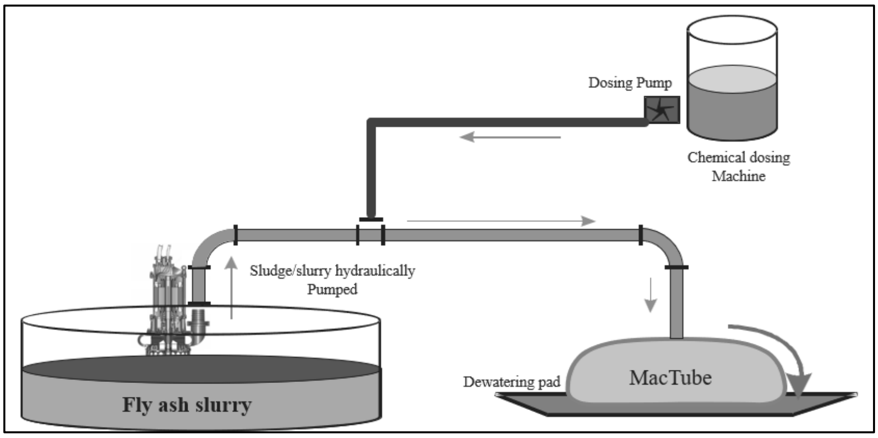


Figure 1: Dewatering of sludge process (Officine Maccaferri, 2017)

Once the geotextile tube is filled and entirely dewatered, it can be removed from its hose network and transported off-site, available for integration into construction activities. The hose network is replaced with an empty tube, to ensure continuity of the dewatering system.

3 Tapping into the potential of fly ash tailings

There are various types of tailings waste available, and these can be identified by their source of origin, i.e., mineral mine tailings and coal fly ash tailings (Lee, 2007). A mineral mine tailings slurry is reported to have a low solid content and high water content when combined with distilled water and a chemical admixture ($CaCl_2$), as compared to a fly-ash slurry, which exhibits a higher solid content (Lee, 2007). Whilst both tailings are abundantly available, the utilization of a fly-ash tailings slurry as infill material for Geotextile Tubes is explored for its potential reutilization in construction practices.

3.1 Disposal of fly ash tailings

Fly ash tailings are deposited following dry or wet disposal methods (Gustafson, 2012). Dry disposal involves the transportation of dampened fly ash (10% water), (Environmental Impact Management Services, 2018), while wet disposal methods require pumpable slurries of 33% solids, 67% liquids (Gustafson, 2012). Both disposal methods have arguably positive and negative impacts on the surrounding environments, however, research studies show that due to the finer particle size of fly ash, wet disposal of fly ash is suggested (Department of Environmental Affairs, 2018). Although this is a preferred storage and disposal method for fly ash slurries, leachate formation, and acid-mine drainage concerns arise in ash dump facilities (Gustafson, 2012). To mitigate the concerns of accidental leakages into the bulk water supply pipelines, on-site dewatering systems are proposed to bulk treat fresh fly ash produced.

3.2 Material properties of fly ash

A study focused on determining the mineralogy of fly ash investigated the leachate concentration of some element groups present in fly ash samples and displayed in Table 1 (Gustafson, 2012). When the results obtained are compared to the World Health Organization's Drinking Water Standards, the potency of fly ash leachate is discovered (Gustafson, 2012). Other elements found in fly ash include Admium (Ad), Chromium (Cr), Strontium (Sr), (Gustafson, 2012). Although these elements exist in small concentrations within a volumetric sample, the presence of these elements have severe effects if mismanaged and untreated (Gustafson, 2012).

Table 1: Chemical composition and leachate concentration of fly ash (Gustafson, 2012)

Element	Fly-Ash Leachate concentration [µg/kg]	WHO Drinking Water Standard Requirement [µg/kg]
As	175	10
Ni	6900	70
Pb	7000	10
Sr	63000	NA

According to ASTM Specification C350-54T, fly ash is accepted for use as an admixture and can be classified into two categories:

Class F : ash produced from bituminous coal and,
Class C : ash produced from sub-bituminous coal containing lignite* (Manz, 1996).

A South African study conducted on coal fly ash samples tested from five different power stations located within the Mpumalanga region, showed that Class F fly ash is largely present (John Alegbe, 2018). Although fly ash can be classified by their composition, mineralogy, and surface chemistry, its physical appearance varies from dark brown to grey, depending on the percent of unburned carbon present in the coal ash (Anjani R.K. Gollakota, 2019). Since the fly ash produced in South Africa can be considered largely bituminous, the dewatering efficiencies of a Class F fly ash slurry are investigated further. Class F fly ash is expected to have the following chemical composition: Ml: Mullite, C: Calcite, H: Hematite, M: Magnetite, and Q: Quartz, GP: Gypsum, α-Fe: Syn Fe, (John Alegbe, 2018). It is further reported that samples exhibited spherical and non-spherical particles, ranging from 0.2-0.25μm in size (Gustafson, 2012). The morphology of the slurries was reported to formulate microspheres once agitated, which resembles the formation of a sludge cake, at a microscopical level, as shown in Figure 2 (Anjani R.K. Gollakota, 2019).

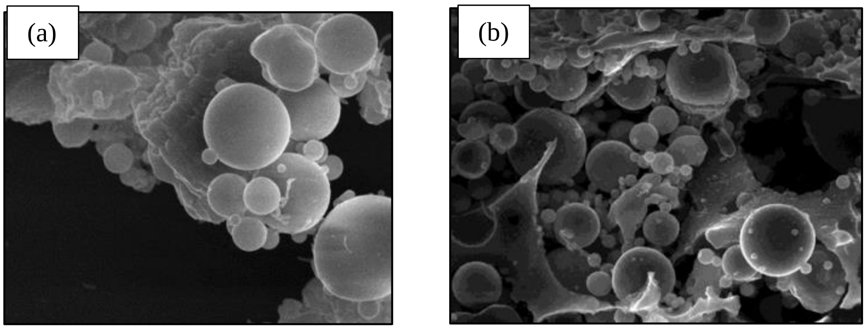


Figure 2: SEM Imaging of Class F Fly ash slurries (John Alegbe, 2018).

3.3 Availability of fly ash tailings in South Africa

South African coal-fired power stations are used as a reference to define the quantity of coal ash produced. Mpumalanga has the highest concentration of coal-fired power stations (66%), while Gauteng comes in second (22%) and Limpopo third (11%) (Department of Environmental Affairs, 2018). It is further reported that coal contributes between 91% and 93% of South Africa's electricity generation. While there are many case studies on the reutilization and integration of fly ash into general construction practice within South Africa, the efforts cannot be seen on a global scale - Europe reports to have successfully reused 90% of all fly ash generated, the China reports 66%, US reports 40%, India reports 13% (Gustafson, 2012) and South Africa reports only 5% on the same matter (Kelley Reynolds-Clausen, 2018).

**Lignite: non-agglomerating coal with high moisture, volatile content, and low carbon content (The Coal Handbook , 2013).*

4 Engineering geofabrics into geotextiles

Geofabrics are textiles engineered to form porous, flexible, planar polymeric fabrics that are used for a variety of applications in the construction industry (Koerner, 1990). The fundamental characteristics of geotextiles have proven to have exceptional results in the following criteria: filtration, separation, protection, barrier, erosion control, reinforcement, and drainage, however, in a Geotextile Tube application, the dewatering and filtration efficiencies are emphasized.

4.1 Characteristics of a geotextile

The technical specifications and manufacturing methods of geotextiles play a significant role in the performance of geotextiles (Gustafson, 2012). Geotextiles are woven or non-woven fabrics consisting of either polypropylene (PP) or polyester (PET) mono-/multi- filament fibres, assembled by needle-punched (N) treatment and thermocalendered (H) processes. These manufacturing methods contribute to the material characteristics displayed in Table 2 (Gustafson, 2012). The chosen sample group was pre-selected based on dewatering research conducted by Gustafson, 2012.

Table 2: Geotextile material characteristics (Gustafson, 2012)

Sample	**Material**	**Material structure**	**Mass per unit area [g/m^2]**	**Thickness [mm]**	**Permittivity [sec^{-1}]**	**Apparent opening size (AOS) [mm]**	**Filtration opening size (FOS) [mm]**
W-1	PP	Slit-film	585	1.04	0.37	0.26	0.170
W-2	PP	Slit-film	462	0.91	NA	0.40	0.37
W-3	PP	Monofilament	298	0.90	0.90	0.42	0.38
W-4	PP	Monofilament	271	0.89	0.51	0.25	0.22
W-5	PP	Monofilament	210	0.40	0.28	0.15	0.14
W-6	PET	Multifilament	813	1.08	0.38	0.17	0.14
W-7	PP	Multifilament	1 117*	1.76*	NA	0.70	0.71

The sample set, W1 to W7, comprised of polypropylene and polyester fibres, with slit film, mono- and multifilament material structure types (Gustafson, 2012). The permittivity of five samples was determined, concluding that these samples have dewatering abilities (Gustafson, 2012). Based on permittivity results, it was determined that the mass per unit area of a geotextile impacts the dewatering and filtration efficiencies of that geotextile (Gustafson, 2012). SEM imaging of monofilament (Figure 3a), multifilament (Figure 3b), and slit film (Figure 3c) is used to determine the apparent opening sizes and filtration opening sizes of the sample set (Gustafson, 2012). Those samples that gave no permittivity readings were described to experience ‘clogging’, whereby fine particles form a sludge cake, restricting the dewatering and filtration efficiencies of the geotextile (Gustafson, 2012).

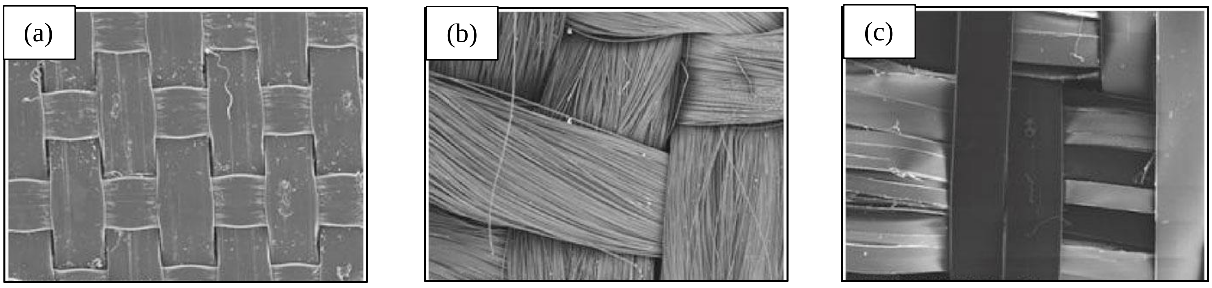


Figure 3: Scanning Electronic Microscopy (SEM) Imaging of Geotextile types [x25 zoom], (Gustafson, 2012)

5 Understanding Geotextile Tube Dewatering Cells

A further innovation of geotextiles revealed the invention of Geotextile Tubes, which are large containment cells traditionally used as breakwater systems in coastal applications (Gustafson, 2012). A Geotextile Tube is formed using critically designed geotextiles suitable for filtration and dewatering. This innovation harnesses the flexibility and permeability of these planar fabrics to form a tube-like, three-dimensional unit, that when hydraulically pumped, forms a containment cell for solids, whilst filtering effluents through apparent openings in the geotextile (Officine Maccaferri, 2017). The solids retained is dependent on the particle size in relation to the apparent opening size of the Geotextile Tube.

5.1 Creating Geotextile Tubes using engineered seam styles

Once the characteristics of a geotextile suitable for dewatering and filtration has been determined, the design and analysis of a Geotextile Tube follows. These tubes are manufactured with critically designed seam strengths, suitable to accommodate pressures created within the tube. Figure 4a and 4b shows the typical Geotextile Tube dimension and seam details (Figure 4b), whilst Table 3 describes the seam styles applicable for geotextiles (Officine Maccaferri, 2017).

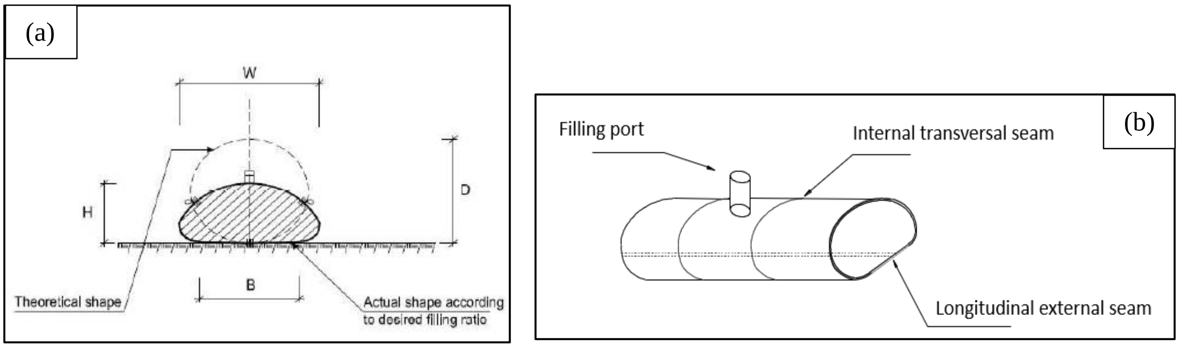
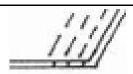
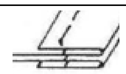


Figure 4: Characteristics of a Geotextile Tube (Officine Maccaferri, 2017)

Table 3: Seam styles and strength (Koerner, 1990)

Seam style	Description		Tensile strength [kN/m]
Prayer seams	Geotextile is stacked without folds and single, double, or triple-stitched along one edge		18-35
J-seams	Geotextile is stacked with one edge folded over and single or double-stitched at the fold		53-123
Butterfly seams	Each layer is folded along the edge before stacking and single or double-stitched		53-123

5.2 Design of Fly Ash Geotextile Tube Dewatering Cells

The analysis of Geotextile Tubes requires design checks for a filled, semi-filled, and unfilled Geotextile Tube, however, the design methodology described below shows approximated values for a filled Geotextile Tube. In terms of the filling methods, the slurry is set to pre-determined specifications, generally 30% solids, and 70% liquids, before being hydraulically pumped through filling ports designed to accommodate a required volumetric inflow over time (Officine Maccaferri, 2017). The bulk density ratio of the slurry ($\gamma_{solids}/\ \gamma_{liquids}$) is approximated to be 1.1 (Officine Maccaferri, 2017). The following material properties of fly ash and Geotextile Tube characteristics were considered for analysing a preliminary design of fly ash Dewatering Cells checks - Consolidated Shape, Circumferential Tensions, and Internal Hydraulic Pressures, assuming a constant pumping rate of 20kPa (Officine Maccaferri, 2017)

Unit weight of fly ash slurry [30% solids, 70% liquids], γ_{dry}	17.4 kN/m^3	(Lee, 2007)
Unit weight of saturated fly ash, γ_{sat}	11.46 kN/m^3	(Lee, 2007)
Specific Gravity of fly ash, G_s	2.1-3.0	(Lee, 2007)

Table 4: Technical Characteristics of a Geotextile Tube (Officine Maccaferri, 2017)

Technical Characteristics	Testing Standard		Unit	Geotextile Tube
Material	-		-	Polypropylene
Mass per unit area of geocomposite	ASTM D-5261	ISO 9864	g/m^2	950
Tensile Strength Main Directions (MD)	ASTM D-4595	ISO 10319	kN/m	200
Tensile Strength Cross Main Direction (CMD)	ASTM D-4595	ISO 10319	kN/m	200
Static Puncture Resistance (CBR)	ASTM D-6241	ISO 12236	N	24000
Permittivity (50mm head)	ASTM D-4491	ISO 11058	s^{-1}	0.5
Apparent opening size	ASTM D-4751	ISO 12956	µm	297
Seam Strength	ASTM D-4884	ISO 10321	kN/m	100
Length	-		m	30
Circumference	-		m	17.2
Maximum Height	-		m	3.40

Reduction factors for the above-mentioned Geotextile Tube, as per manufacturer specifications: *Installation Damage, R_{Fid} = 1.3; Durability, R_{Fd} = 1.0; Creep, R_{Fc} = 1.5; Longitudinal Seam Strengths, R_{Fssl} = 2.0; Circumferential Seam Strengths, R_{Fssc} = 2.0.*

5.2.1. Consolidated Shape of Geotextile Tube using a Fly ash slurry

As the Geotextile Tube is filled, dewatering begins almost immediately. Figure 5a illustrates the geotextile tube after one interval of filling and dewatering whereas Figure 5b illustrates a full Geotextile Tube after approximately four cycles of pumping and dewatering. The following parameters relating to the consolidated shape are determined to be the following: H=2.9m and W=4.8m.

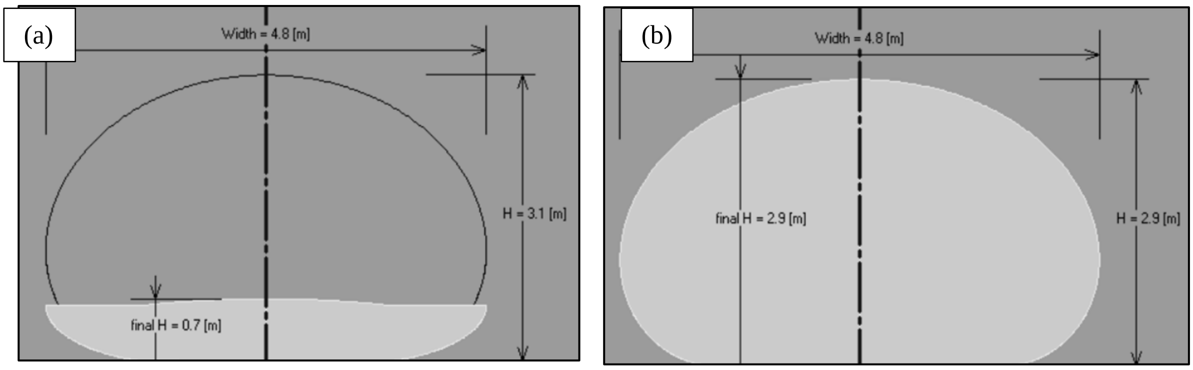


Figure 5a: Geotextile Tube after one round of filling, Figure 5b: Fully dewatered Geotextile Tube at maximum capacity

The theoretical shape of the Geotextile Tube is assumed to have a diameter *D* [m], and when filled, the height is approximated to be 70% of the theoretical diameter, *H* [m]. The actual shape of a Geotextile Tube can further be defined by its base contact width, *B* [m], and its filled width, *W*[m], and respective height, *h* [m]. In terms of assessing the viability of the structural shape of the tube, $\frac{H}{W}$ ratios are determined at intervals of the filling process (Officine Maccaferri, 2017). Approximate $\frac{H}{W}$ ratios at the start of the filling process range between 0.9 and 0.99, and are expected to decrease over time, with $\frac{H}{W}$ ratios of a semi-filled tube ranging between 0.5 and 0.83, and 0.2 to 0.5 for a filled Geotextile Tube (Officine Maccaferri, 2017).

5.2.2 Circumferential surface tension

It is approximated that the total surface tension, T_{max} [kN/m], is determined per square meter, which is applied to the base surface tension, T_b [kN/m^2], which is 10 to 15% of T_{max}, the upper surface tension, T_u [kN/m^2], which is 50 to 70% of T_{max} and the surface tension on the sides which experiences the maximum circumferential tension (Officine Maccaferri, 2017). For the application of Fly Ash Geotextile Tube Dewatering Cells, the following circumferential tensile forces are expected, and the required tensile strength of the geotextile should be less than the tensile strength of the Geotextile Tube in the respective directions (Officine Maccaferri, 2017).

Circumferential Tension along the internal transversal seam	66 kN/m	(Leshchinsky, 1995)
Required Ultimate Tensile Strength in Geotextile	258 kN/m	(Leshchinsky, 1995)
Circumferential Tension along longitudinal seam	44 kN/m	(Leshchinsky, 1995)
Required Ultimate Tensile Strength in Geotextile	170 kN/m	(Leshchinsky, 1995)

In cases where the characteristics of the Geotextile Tube do not meet the required tensile requirements, a custom Geotextile Tube is advised, using a heavier grade of geotextile (Officine Maccaferri, 2017).

*Note: Consider fly ash particle size with respect to the parent material of a Geotextile Tube.

5.2.3 Internal hydraulic pressures

Based on the ultimate tensile strength of the Geotextile Tube per square meter, the internal hydraulic pressure is approximated to decrease over time, with the highest pressure experienced at the initial filling point (Officine Maccaferri, 2017). As the tube dewaters a treated effluent, the pressure reduces to zero kilopascals, until a solid tube-like structure is formed out of retained solids (Officine Maccaferri, 2017).

6 Conclusions

South Africa is identified as a mass producer of fly ash tailings through coal combustion processes implemented during electricity generation (Department of Environmental Affairs, 2018). The ash tailings produced in South Africa are identified as Class F tailings (Manz, 1996), which is fairly potent when compared with drinking water standards (Gustafson, 2012). This explains the need for storing fly ash tailings in ash dump facilities, which are generally on-site or off-site facilities designed to mitigate fly ash leachate formation (Environmental Impact Management Services, 2018). With the increasing demand for sustainable solutions focused on minimizing environmental challenges created through electricity generation, the solutions discussed in this paper are aimed at bulk-treating fly ash tailings through Geotextile Tube Dewatering Systems. Although a dampened dry disposal method for fly ash is largely used in South Africa, a wet disposal system is proposed by redefining Geotextile Tubes, tailoring its characteristics to create high dewatering and filtration efficiencies. This requires an in-depth understanding of geotextile properties and manufacturing methods that contribute to the overall performance of Geotextile Tubes (Officine Maccaferri, 2017). Formulating Geotextile Tube dewatering systems at South African electricity generation facilities shows great potential for utilizing treated fly ash in a variety of geotechnical applications.

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