Value added utilisation possibilities of coal combustion products in South Africa

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DECLARATION

I, Christine Schutte, declare that this research report is my own, unaided work. It is being submitted in fulfilment for the degree Master in Engineering (MEng) in Chemical Engineering at the Potchefstroom Campus of the North West University. Information obtained from other academic sources has been referenced accordingly. This document has not been submitted before for any degree or examination to any other academic institution.

Christine Schutte
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ABSTRACT

The disposal of coal combustion products (CCP's), which includes coal ash and the new combustion product Flue Gas Desulphurisation (FGD) gypsum, causes significant environmental and economic difficulties. Only a small fraction of the coal ash currently produced in South Africa is utilised, whilst the bulk of it is held in ash storage facilities. The maximum possible utilisation rate for Eskom was in the range of 18% or 5.8 Mt for the 2015/2016 financial year. To reduce the environmental and economic impacts of the disposal of the coal ash and future FGD gypsum, alternative utilisation of these products was investigated. The proposed quality of FGD gypsum that can be expected from different South African limestone sources were evaluated. A Polish limestone and corresponding FGD gypsum sample was used as a base case in creating synthetic gypsum samples from three South African limestone samples. The aim of this exercise was to create gypsum samples that will replicate actual FGD gypsum samples from the wet FGD process. It was found that the gypsum quality correlates well with the limestone purity with a deviation of around 1-2% in laboratory conditions. Kusile will produce 900 000 tonnes/annum FGD gypsum which covers the demand for all the gypsum used in the cement and agriculture industry. It is important to use limestone of a high and consistent purity to ensure FGD gypsum end product suitable to use in the wallboard industry. Samples of ash from both Poland and South Africa were studied and compared to the South African legislation parameters. This comparison gave way to knowledge portraying that the fly ash from Poland and South Africa show strong similarities in terms of elemental composition and heavy metals. A comparison was drawn between the legislation regulating CCP in both South Africa and the European Union. This indicated that South African waste classification practises are more stringent in the current time and perhaps in environmental legislation terms a few years behind. The classification of CCP's in South Africa hinders the development of products and the utilisation thereof. The classification of European Union CCP's as by products enables the utilisation of it in a bigger spectrum of applications. The way forward in terms of waste legislation barriers in South Africa has been discussed. Global utilisation strategies cannot be implemented locally without considering South African legislation, high transport costs and a lack of proper infrastructure, additional capital and operational expenditure and stakeholder engagement. The proposed recommendations include offset interventions where CCP's can be used as thermal panels in low cost housing units. Coal ash can be successfully utilised in mine backfilling, road construction and agriculture solutions pending a change in legislation with pilot studies and the development of Norms and Standards. The work performed in this study contributes to the advancement of the utilisation of FGD gypsum and fly ash.

Key words: Coal Combustion Products, fly ash, FGD gypsum, industrial application, waste legislation.

PREFACE

Sulphur dioxide (SO_2) emitted by the burning of coal in the electricity generation process is a harmful gas to both the environment and human health. The Department of Environmental Affairs in South Africa enacted more stringent air quality standards for scheduled industries, including Eskom, to be met by 2020. In order for Eskom to meet the terms of these regulations it was decided to install flue gas desulphurisation (FGD) plant at the new Kusile and Medupi power stations. The FGD plant at Kusile power station will be fully functional from the commencement of power generation, whilst Medupi will be retrofitted with an FGD plant. The FGD process at Kusile will generate around 900 000 tons/annum of saleable product FGD gypsum.

South Africa has a vast coal reserve which it has used over the past 5 decades in large coal-fired power stations which still supply 77% of the generated electricity (Eskom, 2017). The coal in South Africa has a very high ash content and subsequently leads to the disposal of large amounts of coal ash at each power station (Kruger & Krueger, 2005). In the past the land adjacent to the power stations was reasonably priced and this facilitated inexpensive disposal of ash in large ash dams. The location in remote areas of these landfills called for no interference from the public to minimise the aesthetic and environmental impact. The significant distance from economical centres and other industrial activities resulted in high transport costs which played an additional undesirable role in removal (Kruger & Krueger, 2005). The Eskom Integrated Report for the 2015/2016 year showed that 32.6Mt of ash was produced in this period, and only 8% of that was recycled.

Innovative solutions will have to be investigated to overcome the storage concern of coal combustion products at Eskom power stations, in particular fly ash. By using these coal combustion products in engineering projects, the environmental concerns can be addressed.

This dissertation is divided into six chapters. In *Chapter 1* the background of this study is introduced and the research objectives are presented. A literature review with a general overview of coal combustion products with characteristics and uses are provided. *Chapter 2* describes the international best practises and utilisations of coal combustion products, specifically focusing on fly ash and FGD gypsum. *Chapter 3* contains the South African practise on coal combustion products utilisation and disposal as well as a comparative study with the European Union, in particular Poland. This chapter also includes a comparison of the legislative requirements that governs the classification and utilisation of CCP's in a European and South African context. *Chapter 4* describes the experimental procedure and methods of creating laboratory gypsum from available South African limestone sources and the testing of the quality according to three methods. *Chapter 5* describes the analysis and shows the results and discussions of the experimental work. *Chapter 6* contains the conclusions and recommendations of the study. The information in the preceding chapters was used to establish a list of recommendations on the future utilisation prospects of CCP's in a South African context.

The work performed in this study produced a document that will advance the uses of FGD gypsum and fly ash and to create situations where Eskom, the environment and the South African population can benefit from these best management practices.

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Finally, I would like to thank God for gracing my life with opportunities. It is important to believe in things that we cannot measure or hold in our hands, and I want to thank Him for the courage to take chances in life. Always believe in what you pray for because miracles start to happen when we give more energy to our dreams than to our fears.

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1. OVERVIEW

1.1 INTRODUCTION

Global population is set to increase from 7.6 billion in 2017 to around 10 billion in 2050 (United Nations, 2017). The increase in energy demand can be attributed to population and economic growth. Energy is essential to the development of modern economies where a robust supply is required. There is still a high global dependence on fossil fuels for energy generation but renewable energy resources have gained momentum in the last few years. This shift of supply is credited to the need for the reduction in greenhouse gas emissions, a change in the consumer behaviour and the innovation in energy options (New Climate Economy, 2014).The BP Statistical Review of World Energy Report released in June 2017 showed that primary energy consumption rose by 1% in 2016 and the CO_2 emissions increased by only 0.1%. There was a reduction of 1.7% of global coal consumption in 2016 and also a decrease of 6.2% in coal production due to the competitiveness and increasing availability of renewables and natural gas. The share of coal in the global primary energy mix was 28.1% in 2016. Wind and solar energy showed a combined growth of 14.1% in 2016.

The burning of coal for power generation supplies 77% of the electricity needs in South Africa (Eskom, 2017). Coal reserves in South Africa are estimated at 53 billion tonnes, which translates to a supply of coal for another 200 years (Eskom, 2017). It makes economically sense for countries that have abundant coal resources to choose coal fired electricity generation over renewable energy sources (Yao *et al*., 2015). South Africa has a high level of renewable energy potential, especially in terms of solar and wind energy. In line with the Independent Power Producers (IPP) programme the country is set to introduce 17 800 MW of renewable energy into the grid by 2030 (Integrated Resource Plan, 2010). Eskom owns eleven base load and three return-to-service power stations, mostly situated in the Highveld region. The fourteen stations mentioned excludes the two new build base load stations, Kusile and Medupi, which is still under construction and locations indicated on Figure 1-1. Both Medupi and Kusile will be utilising dry cooled technologies to minimise the impact on South African water resources.

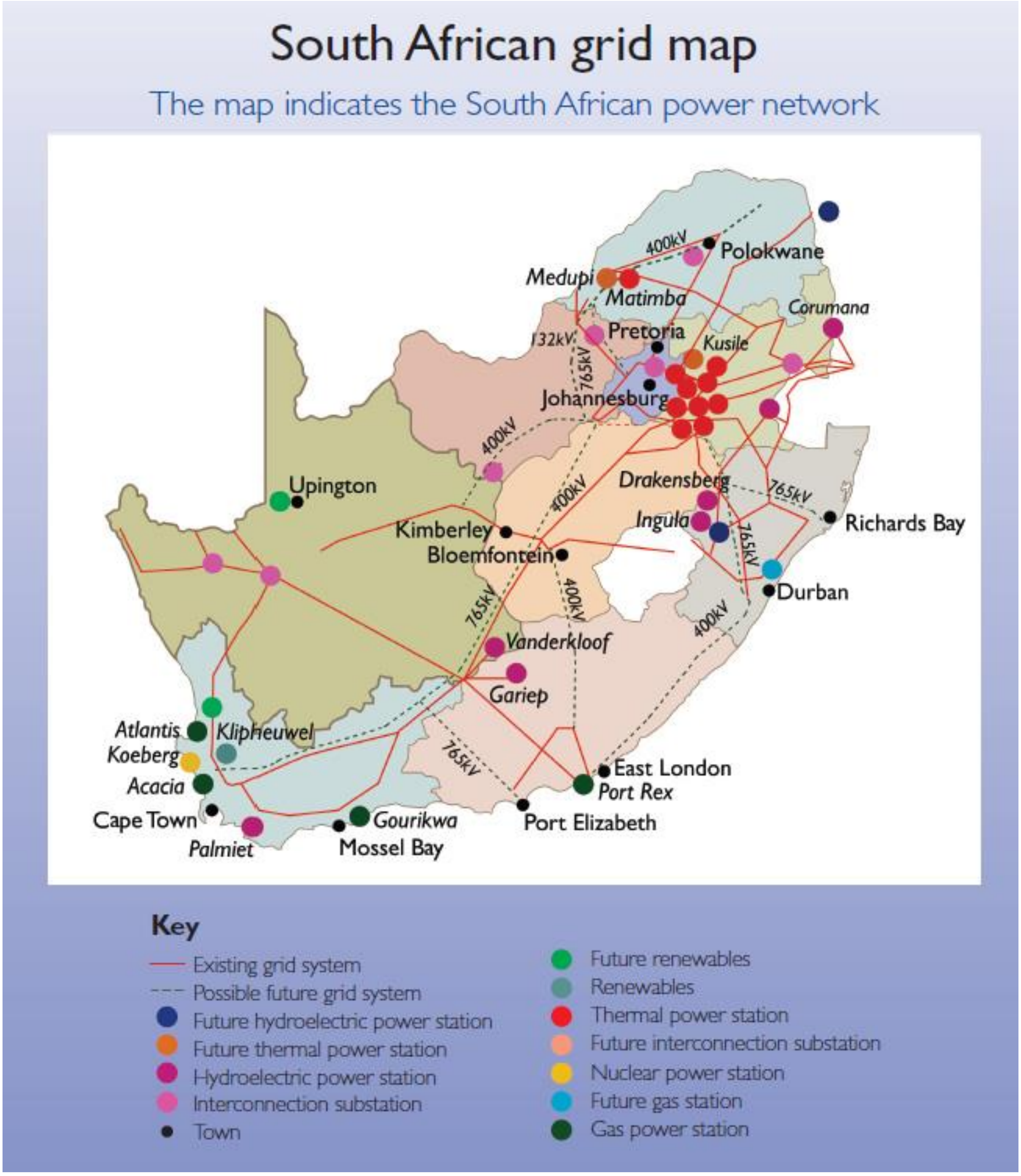


Figure 1-1 Eskom electricity grid map (Eskom Financial Results, 2011.)

The 2015/2016 Eskom Integrated Report showed that 32.6Mt of ash was produced during that financial year. Only 8% of that was recycled and the rest was placed onto landfill sites. Improper disposal of coal ashes can lead to environmental concern by air pollution and groundwater contamination. The recycling and re-usage of fly ash is a good alternative to disposal and has environmental and economic benefits. The substitution of cement by fly ash in the USA alone, saves more than 55 trillion Btu of energy and leads to a reduction of GHG emissions by 9.6 million tonnes CO_2e (Benson *et al*., 2009).

Kusile will be the first power station in South Africa that will have an installed flue gas desulphurisation (FGD) plant to reduce sulphur emissions by up to 90% (Eskom, 2012). Medupi power station will be retrofitted with an FGD plant after commissioning of the power station. FGD systems can be classified into wet and dry systems, with the wet FGD (WFGD) process used considerably more because of its high desulphurisation performance and reliability (US EPA, 2015). Within the wet system a scrubbing liquid, containing an alkali reagent, is used to absorb the SO_2. Limestone is normally used within these specific systems as the reagent, as will be the case at both Kusile and Medupi power stations. The limestone scrubbing in the WFGD systems at both Eskom power stations will be a regenerable process that will produce a saleable product, FGD gypsum.

The Department of Environmental Affairs (DEA) granted Eskom a reprieve in complying with the emission standards in early 2015. These postponements have been granted by the DEA to give Eskom, and other industries, some additional time to acquire new technologies and to retrofit older stations. A condition of the postponement of compliance until 2020 is that Eskom must devise offset interventions and implement these programmes to reduce particulate matter pollution in the ambient environment.

Innovative solutions will have to be found to address the storage concerns of Eskom's coal combustion products. Utilisation of coal combustion products in a global context will be examined and scrutinised to assist in increasing the Eskom product recycling rates. Fly ash is globally mostly used in the construction and cement industry, and it is also used in large volumes in road construction and mine backfilling. FGD gypsum is commonly used as a substitute for natural gypsum in the wallboard manufacturing industry. It is important to consider the classification of South African fly ash sources when compared to International utilisation.

The purpose of this study is to provide a comprehensive overview of the current state of knowledge and usage of CCP in some parts of the world, South Africa and Eskom in particular. In addition the characteristics of gypsum from flue gas desulphurisation (FGD) and fly ash derived from coal combustion for electricity generation will be discussed in this chapter. The literature review delivers information on all utilisation possibilities for these products. Recommendations will be provided on the bulk utilisation possibilities of CCP's in an Eskom context. The expected FGD gypsum quality, based on South African limestone sources will be discussed.

1.2 AIMS AND OBJECTIVES

This dissertation will provide insight on the utilisation of coal combustion products, the legislation that governs its handling and disposal and potential alternative uses in South Africa for the future. The objectives of this study include the following:

- identifying all the possible and or potential uses of FGD gypsum and fly ash in a South African context and market based on International best practise;
- perform a comparative study on the legislation, utilisation and management of CCP's between Poland and South Africa, also India and South Africa and
- determine whether the quality of Eskom FGD gypsum (within a pre-specified limestone quality range) makes it applicable to utilise in South African industrial sectors.

1.3 LITERATURE REVIEW

Coal Combustion Products (CCP's) has become a commonly used term for the solid materials resulting from the combustion of coal for power generation and other industrial processes. The four main CCP's components are fly ash, flue gas desulphurisation (FGD) gypsum, bottom ash and boiler slag. The focus of the study will be on fly ash and FGD gypsum. Each of these products consists of different properties that can be applied in different applications. These applications add value to both the international and domestic sectors such as the construction, agriculture and mining industries.

The burning of coal in combination with pollution control technologies generates large quantities of CCP's (Kalyoncu & Olson, 2001). A study by the Electric Power Research Institute (EPRI) showed that 119 million tonnes of CCP's were produced in the US in 2007, 47% of which was utilised and the remaining 53% was stored or disposed (Benson *et al*., 2009). CCP's have desirable attributes and it can be used as a replacement for natural materials in the construction and other industries. The global spike in interest of sustainable construction and development ensured an increase in utilisation of CCP's. The application of CCP's rather than natural construction products provides savings in energy and a reduction in water use. The main reason for this is the reduction of emissions and resources required for mining, processing and transformation of natural materials (Benson *et al*., 2009).

Solid materials included in CCP's are fly ash, bottom ash, boiler slags and flue gas desulphurisation (FGD) gypsum. Fly ash represents almost 58% of the CCP's produced worldwide, FGD gypsum amounts to 24%, bottom ash 15.5% and boiler slag the remaining

2.5%. Amongst the four solid materials, fly ash and FGD gypsum have the highest utilisation rates (Kalyoncu, 2001). The four solid materials comprises of the following:

a. Fly ash is fine fraction particulate matter carried out of the boiler by the flue gas and captured (99%) by dust collection systems.
b. Bottom ash is the larger ash particles that accumulate at the bottom of the boiler.
c. Boiler slag is the inorganic material collected at the bottom of the boiler, quenched in a water filled pit and finally presented as particles that resembles sand.
d. FGD gypsum is the product of flue gas desulphurisation at coal fired power stations where wet scrubbers, with calcium carbonate as scrubbing agent, are used in conjunction with forced oxidation to reduce SO_2 emissions.

CCP materials have different applications, depending on the chemical composition of the product. CCP's are utilised in the cement and concrete, agriculture, mining, road construction and wallboard industry. When CCP's are used as construction materials it enhances the chemical durability while simultaneously reducing costs. FGD gypsum used in the agriculture industry can provide sulphur required for healthy plant growth (Kalyoncu & Olson, 2001).

1.3.1 FGD Gypsum

Since 9000 BC natural gypsum has been used in the construction industry, mostly as a plaster. According to Eurogypsum, the voice of the European gypsum industry, natural gypsum can be used for the following:

- As a fire retarder in mostly plastic products;
- in PPC cement as a retarder and to control expansion;
- as a source of calcium and sulphur in agricultural land applications;
- in some baking practices as a calcium source and a baking aid;
- modelling materials in tooth restorations and
- in conjunction with glass to fabricate architectural decorations.

Natural gypsum is widely used in a range of applications, as mentioned, and FGD gypsum can be used in most of these as a replacement material. The main uses for gypsum presently include the use of it in building materials such as plasterboards, which includes wallboards and drywalls. The pioneer plasterboard plant was erected in the USA in 1901. In 1908 the plasterboard technique was improved and patented as a gypsum core with a layer of paper on each side of the board. Since this improvement, the manufacturing of plasterboard in a similar fashion has increased globally, and in Europe alone there are more than 200 manufacturers of these products.

1.3.1.1 Characteristics of FGD gypsum

Gypsum can occur in two natural forms, anhydrite ($CaSO_4$) and gypsum dehydrate ($CaSO_4$•$2H_2O$). The chemical difference between these two forms is the two molecules of crystallised water (Rouppet, 2003). The most common form of natural gypsum ($CaSO_4$•$2H_2O$) is a hydrous calcium sulphate which in a pure form is normally white. FGD gypsum is usually termed as synthetic gypsum, due to its production within WFGD scrubbing systems that uses limestone reagents and forced oxidation processes. FGD gypsum is the largest contributor to the synthetic gypsum market worldwide and it is freely substituted for natural gypsum due to its similarities in chemical composition (Ladwig, 2006). FGD systems installed in industries globally are typically wet systems and the calcium in the reagent reacts with the sulphur in the flue gas, and when forced oxidation is introduced in the system, calcium sulphate dihydrate ($CaSO_4$•$2H_20$) is formed.

In the United States most gypsum is calcinated, to remove one and a half of the waters of hydration, to yield calcium sulfate hemihydrate ($CaSO_4$•$0.5H_2O$). The hemihydrate, which is in powder form, rehydrates when water is added to recrystallize and harden (Ladwig, 2006).

The FGD process at the power station utilises lime ($CaCO_3$) as scrubbing material and when added to water, an alkaline slurry forms. The alkaline slurry is sprayed in the absorber and reacts with the SO_2 in the flue gas. The simplified reactions of the chemical process that occur simultaneously are illustrated as shown:

SO_2 dissociation:

$$SO_{2\,(g)} \rightarrow SO_{2(aq)}$$

$$SO_{2(aq)} + H_2O_{(l)} \rightarrow H_2SO_{3(aq)}$$

$$H_2SO_{3(aq)} \rightarrow H^+{}_{(aq)} + HSO_3{}^-{}_{(aq)} \rightarrow 2H^+{}_{(aq)} + SO_3{}^-{}_{(aq)}$$

Lime (CaO) oxidation:

$$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2\,(aq)}$$

$$Ca(OH_2)_{(aq)} \rightarrow Ca^{2+}{}_{(aq)} + 2OH^-{}_{(aq)}$$

Now that both have dissociated the following occurs:

$$Ca^{2+}{}_{(aq)} + SO_3{}^-{}_{(aq)} + 2H^+{}_{(aq)} + 2OH^-{}_{(aq)} \rightarrow CaSO_{3(aq)} + 2H_2O_{(aq)}$$

During forced oxidation, the following will occur:

$$SO_3{}^{-}{}_{(aq)} + \frac{1}{2}O_{2\,(g)} \rightarrow SO_4{}^{2-}{}_{(aq)}$$

$$SO_4{}^{2-}{}_{(aq)} + Ca^{2+}{}_{(aq)} \rightarrow CaSO_{4\,(s)}$$

Natural gypsum and FGD gypsum are chemically very similar in composition, there are however a few differences that can either be beneficial or detrimental in the substitution of the products. FGD gypsum has considerably higher moisture content and a finer grain size, which in comparison with natural gypsum will influence the transportation, handling and processing (Berland, 2010). The finer grain size of the FGD gypsum requires less grinding to make it useable.

FGD gypsum is a very stable product and not harmful to the environment. It is not subject to decomposition, biodegradation or bioaccumulation. FGD gypsum has a smaller amount of impurities compared to natural gypsum, with 90-99% compared to 66-98% purity concentration for natural mined gypsum (Chen *et al*., 2008). FGD gypsum impurities include ash and soluble salts, which may have an effect on the colour of the product and this, can lead to an undesirable product for some end-users. The soluble salt content can be controlled by washing the FGD gypsum product before drying it to reduce the moisture content (Ramme & Tharaniyil, 2004). Natural gypsum sometimes contains impurities such as clay, soluble salts or other minerals.

1.3.1.2 Utilisation of FGD gypsum

Proposed more stringent regulations for coal fired power generation emissions will result in an increase of installed FGD systems and ultimately in FGD gypsum. The volume of FGD gypsum in the US nearly doubled between 1987 and 2000, with the utilisation rate also increasing from 1% in 1987 to 20% in 2000 (Berland, 2010). It is essential to develop new markets and safeguard existing markets to further increase the utilisation of FGD gypsum. Transport and logistics are the most important barriers to overcome to increase utilisation (Smith, 2006).

Wallboard

Internationally high quality FGD gypsum is increasingly replacing natural gypsum in the wallboard manufacturing industry. By encouraging this replacement, it ensures a more consistent quality of gypsum to the wallboard manufacturer, natural resources are preserved and landfill costs and space are avoided (Smith, 2006). Even though gypsum used in the wallboard manufacturing industry increased globally, it is only industrialised countries that use gypsum mostly for wallboard panels. In developing countries gypsum is generally used to manufacture cement or plaster products. The 2012 end-use data for gypsum showed that the primary use for gypsum in a global context is to produce cement and concrete, at a rate of almost 50%. The manufacturing of plaster products and gypsum wallboard accounts for 30% of gypsum use (USGS, 2015).

FGD gypsum can replace natural gypsum in the wallboard production industry, on condition that the plant is fitted out to accept it as a raw material, especially in situations where the colour variations is not important because it is covered with sheeting on both sides. A general guide of specifications for FGD gypsum used in wallboard in the US is shown in Table 1-1 (Ramme & Tharaniyil, 2004). The specifications will be different between manufacturers and this is only used as a general guide in the US. A high purity of above 95% is required to produce wallboard with a lower weight and it will lower the potential for defects in the manufactured product. The inherent moisture content of the FGD gypsum can impact the handling and transportation of the material negatively and must be kept to a minimum.

Table 1-1. General Specifications for FGD use in gypsum wallboard in the US (Ramme & Tharaniyil, 2004).

Property	**Range in Specification**
Purity, $CaSO_4 \cdot 2H_2O$ (min)	92 - 97 (wt. %)
Fly Ash (max)	1.0 (wt. %)
SiO_2 (max)	1.0 (wt. %)
$CaSO_3$ (max)	0.5 - 1.0 (wt. %)
Free moisture (max)	9 – 15 (wt. %)
Particle size (average)	9 – 70 µm
Chloride (max)	100 – 400 ppm
Sodium (max)	25 – 250 ppm
Total water soluble salts (max)	325 – 500 ppm
Blaine surface area (max)	3000 – 3500 cm^3/g
pH	6 – 8 pH units

Agriculture

The use of FGD gypsum in agriculture was largely promoted and researched in the mid 2000’s by the Electric Power Research Institute (EPRI). EPRI found that the potential use for FGD gypsum in the agricultural network is very promising. The overall health of soil in South Africa and globally will remain a concern as it is influential in securing food resources and will play a significant role in water and groundwater quality. Population growth has increased the need for crop yields globally, which in turn leads to rigorous farming practices that can cause depletion of soil (Greenleaf Advisors, 2013). In the US it was found that FGD gypsum, if properly applied, is a useful additive to problematic soil. FGD gypsum can assist in rectifying these soils, which in turn can generate higher crop yields (Chen *et al*., 2008).

The principal function of FGD gypsum in land application uses is to improve soil chemical and physical conditions (Ladwig, 2008). It has the following benefits:

1. Reduction of surface soil acidity.

Plants can normally take up more nutrients when the pH is closer to neutral. The optimum pH for crop production is between 6 and 7 (Ladwig, 2008). A few studies researched the ability of FGD gypsum products to neutralize acidity and increase plant growth. Limestone ($CaCO_3$) is normally used as a fertilizer to increase soil pH, and one of the problems of using calcitic limestone is that the reactive compound in it is very insoluble. In order for calcitic limestone to perform a remediating effect on soil pH the soil had to be disturbed for the limestone to reach deeper profiles. The benefit that FGD gypsum products had over calcitic limestone was that the $CaSO_4$ in the FGD gypsum is considerably more soluble than $CaCO_3$, and thus had the potential to reach more of the lower profile soils (Clark *et al*., 2001). The soil surface did not have to be disturbed when the FGD gypsum was used, and the subsoil still benefitted. The increased Calcium and Sulphate concentrations that could leach into lower profiles ensured that more roots got nutrients and promoted root growth into the subsoil (Clark *et al*., 2001). This in turn leads to an increase in plant yield.

2. Source of plant nutrients.

Plants require several micro- and macronutrients for growth. FGD equipment successfully removes sulphur from flue gas and as a result the sulphur content in the atmosphere decreased in the US over time. Fertilisers containing additional sulphur became very economical as crop yield responded very well to sulphur additions in the US (Ladwig, 2008). FGD gypsum has very high sulphur content and was utilised direct as a soil fertiliser. The nutrients added in land applications were dependent on the chemical composition of the FGD gypsum product. Normally the macronutrients added by using FGD gypsum is calcium and sulphur, but it can also add other nutrients depending on the composition.

EPRI's research showed that the addition of FGD gypsum was beneficial to crops like sweet potatoes, peanuts, roses, blueberries and other growing in soils with low pH values, or soils that required high quantities of soluble calcium for fruit production. EPRI also found that the effect that the addition of FGD gypsum has on the improvement of nitrogen use efficiency in crops can be a promising research topic. Research in Brazil showed that corn and wheat recovered more nitrogen after increased rooting due to the addition of FGD gypsum in the subsoil. In addition to this nitrogen fertiliser is becoming more expensive in the US due to an increase in energy costs. Consequently if FGD gypsum addition can increase the nitrogen use efficiency in plants it can become more valuable (Ladwig, 2006).

3. Improving physical properties of soil.

The addition of FGD gypsum in land applications can have dual benefits by acting as a fertilizer and a conditioner for soil. High levels of sodium and magnesium tends to hydrate and disperse soil particles. Adding FGD gypsum to dispersed soil particles provides soluble calcium that has the ability to improve the flocculation of soil particles (specifically clay), and keeps the soil crumbly, enhancing the penetration of water and allows roots to easily penetrate lower layers (Clark *et al*., 2001).

Due to the FGD gypsum's influence on the clay dispersion it is a very effective additive to reduce erosion (Ladwig, 2006). Surface soil crusting is the destruction of the soil surface structure due to the impact of raindrops, and this can often be prevented with the application of FGD gypsum (Clark *et al*., 2001). FGD gypsum in land applications can possibly increase water infiltration rates of soils that may be prone to crusting and aggregate dispersion (Chen & Dick, 2011).

4. Reducing phosphor and nitrogen concentrations in surface water runoff.

Runoff from agricultural activities, golf courses and other human activities can produce excessive amounts of phosphor and nitrogen nutrients to streams and other water bodies (Ladwig, 2008).. The excessive growth of algae in water bodies can lead to oxygen depletion which in turns lead to loss of aquatic life. FGD gypsum has the potential to reduce phosphor and nitrogen when used in land applications. It is essential to monitor the use of FGD gypsum to ensure that the phosphor is not overly reduced to inhibit plant growth (Ladwig, 2006). It is stated in the EPRI report that studies generally favoured the reduction of phosphor in runoff by using FGD gypsum in small scale studies rather than large basin studies. It was recommended that more field studies must be performed to research this potential.

5. Alleviation of sodic soils.

Sodic soils have excessive concentrations of exchangeable sodium which causes the soil to be unstable, impedes water infiltration and leads to compromised crop production, poor soil structure and weak plant growth environments. Sodic soils can be ameliorated by applying FGD gypsum that will displace the sodium and make solutes available which will increase the electrolyte concentrations. The rate of FGD gypsum dissolution (compared to agricultural lime) will assist in the reduction of clay dispersion and increase the infiltration rate and hydraulic conductivity (Ladwig, 2008). A combination of calcium chloride or sulphuric acid with FGD gypsum can reduce the amount of water required and the time needed to attain reclamation (Chen & Dick, 2011).

The report by Clark *et al.* (2001) showed that the following constraints can be encountered with the use of FGD gypsum in agricultural land applications:

- FGD gypsum does not generally increase the pH of soil that much, it will mostly increase with the addition of $CaCO_3$, CaO and $Ca(OH)_2$ which is normally added as a stabilizing agent to the FGD gypsum.
- FGD products must be used in moderation in land use applications to limit an excess of soluble salts, which can be detrimental to plant growth.
- FGD products contain high levels of calcium which may theoretically cause imbalances in levels of nutrients in the soil such as magnesium, potassium and phosphor.
- FGD gypsum contains high levels of sulphate and calcium, so it is recommended to use it in moderation in land applications, as to not let it accumulate in excessive amounts in plants and soil.
- The prospective threat of trace element contamination in water and plants by using FGD gypsum in agricultural land applications is a major concern. Reports have shown that when trace elements of toxins appeared in soils modified by the use of FGD gypsum, it was well below recognised standards and often below undetectable.

Clark *et al*. (2001) found that when FGD gypsum products are used suitably, it will have a beneficial effect on agricultural land.

Rouppet (2003) found that apart from the advantages established by EPRI on the use of gypsum in soil it also enhances water use efficiency. His research showed that there is 25%-100% more water available in soils treated with gypsum which in turn leads to less irrigation water needed to achieve similar results. His research also showed that gypsum went into solution almost immediately when subjected to either rain or irrigation water. *I*t is thus a convenient calcium compound to use in soil amelioration. In addition gypsum is inexpensive and can be found organically or synthetically.

Construction

Uncalcined FGD gypsum is used as an additive to cement, at a ratio of 2% - 6%, to act as a retarder and to enhance grinding characteristics of the clinker (Ramme & Tharaniyil, 2004). In 2004 in the US the cement and concrete industry only accounted for about 9% of total utilisation, but this sector represented around 50% - 60% of global gypsum use. It is mostly used in these sectors in countries where wallboard has not been well established. FGD gypsum is not emitting any radiation and can safely be used in the production of construction materials (Eurogypsum, 2016).

Other uses

1. Remediate reclaimed tidal lands

Urban areas in China are located along the coast or main delta areas such as the Yangtze River. The Yangtze plain advances into the East China Sea at a rate of two kilometres per century according to estimations. River delta land has been reclaimed and the tidal land requires desalination before restoration is accomplished. Natural processes of rainfall leaching and plant community succession can take decades to remediate these areas. A study performed by Li *et al* (2015). over a 2 year time frame, showed that by utilising FGD gypsum as a soil amendment can accelerate the desalination process. They found that the FGD gypsum increased the amount of calcium at the soil cation exchange sites, resulting in an increase of salt leaching efficiency, plant diversity and plant growth. Their conclusion showed that FGD gypsum can effectively remediate saline soil conditions of reclaimed tidal lands.

2. Fire resistant panels

A study was performed by Leiva *et al*. (2010) on manufacturing fire resistant panels composed from 100% FGD gypsum material obtained from two Spanish power stations. The panels were subjected to different physical, chemical, mechanical, fire resistant and environmental tests with the results compared to similar products manufactured from commercial gypsum. The results showed that the panels are not water resistant and the mechanical strength was a bit lower than commercial gypsum product, that can be attributed to lower calcination temperatures. The 100% FGD gypsum showed higher insulation capabilities, whilst tests performed on the panels showed no environmental or leaching complications.

3. Gypsum blocks

Natural gypsum has been used as a raw material for gypsum block, an eco-type and energy saving material, in China. The poor water resistance capability of FGD gypsum has hindered the use of it in these construction blocks. Attempts have been made in coating the finished blocks with a water-resistant material to improve its weather resistance. The cost of these coatings made the finished products unaffordable. Zhao *et al.* (2012) proposed the preparation of a water-resistant agent consisting of granulated blast furnace slag, high calcium fly ash and some additives. The water-resistant agent was mixed with FGD gypsum to form a modified gypsum powder which could then be used in the gypsum block. The study concluded that the mixture agent significantly improved the water resistance of the FGD gypsum material

1.3.1.3 Gypsum quality testing

It is very important to continuously ensure the chemical and physical characteristics of FGD gypsum within a range of specific parameters. The end use of FGD gypsum will be strongly dependent on the characteristics of the material. The gypsum should be continuously analysed and monitored to assure high quality FGD gypsum from coal fired power stations.

The Indian Standard Methods of Test for Mineral Gypsum (2^{nd} Revision), IS: 1288-1982, prescribes the method of testing for mineral gypsum. The American Society for Testing and Materials (ASTM) standard C471-01: *Standard Test Methods for Chemical Analysis of Gypsum and Gypsum Products*, provides test methods that cover the chemical analysis of gypsum and related gypsum products. Neither the Indian Standard or the ASTM standard is focused on FGD gypsum, both are specifically developed to test natural gypsum sources. VGB Powertech released an instruction sheet in 2008 on the analysis of FGD gypsum (VGB M-701). The analysis includes the chemical analysis of FGD gypsum constituents and all other properties as set out by Eurogypsum, ECOBA, VGB PowerTech and Bundesverband der Gipsindustrie. The instruction sheet shows that the quality of the FGD gypsum should be of a quality that it can be used as a direct replacement to natural gypsum during the production process.

1.3.2 Fly ash

The combustion of coal remains a major source of power generation globally, especially in countries with an abundant supply of coal sources, in particular China, the US and India. When there is a profuse amount of coal fields still available it makes economically sense for these countries to choose coal fired electricity generation above expensive natural gasses and renewable energy sources (Yao *et al*., 2015). China is the largest consumer of coal for electricity generation in a global context with 50.2% of all coal consumed in 2012. Other countries in the list of top consumers are USA, India and South Africa. The top ten coal consumers of 2012 can be seen in Figure 1-2. According to Yao *et al.* (2015) using this data a more accurate estimation of annual fly ash generation globally is around 750 million tonnes.

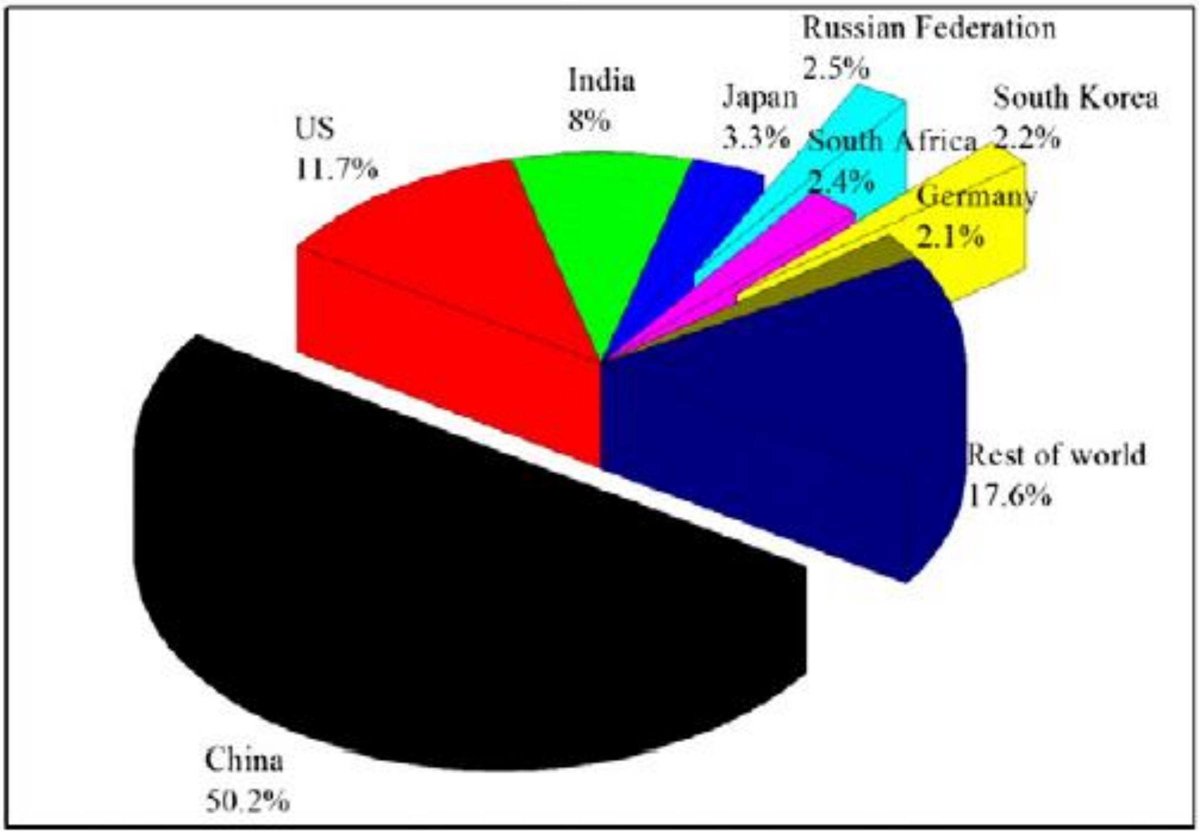


Figure 1-2 - Coal consumption worldwide in 2012 (Yao et al., 2015).

The BP Statistical Review of World Energy (2017) showed that world coal production fell by 6.2% in 2016, whilst consumption fell by 1.7%. The coal consumption per region for 2016 (BP, 2017) is shown in Figure 1-3. The downward trend is by virtue of the heightened interest in renewable energy sources.

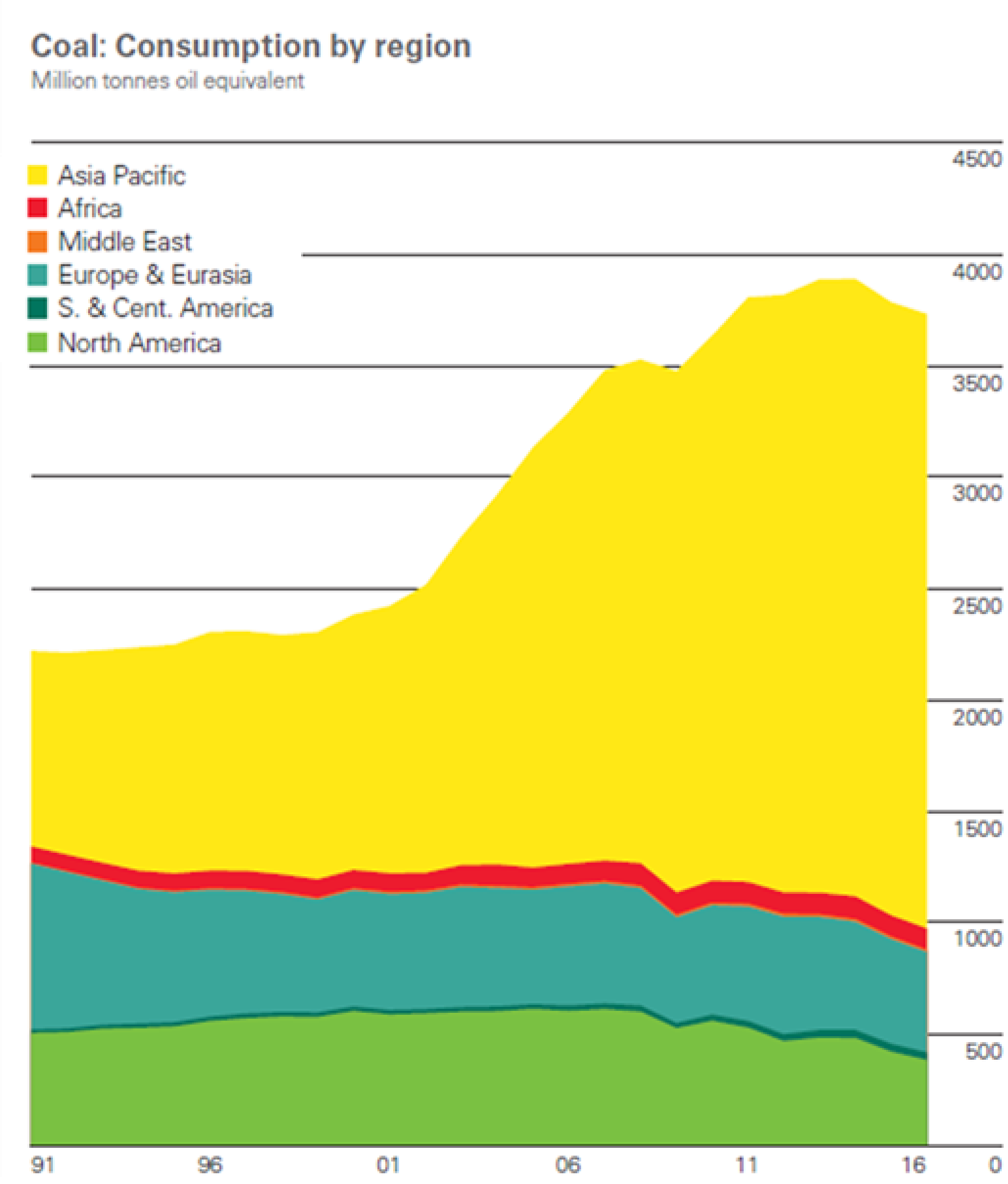


Figure 1-3 Coal consumption per region: 2016 (BP, 2017).

Fly Ash is the coal combustion product derived in thermal power plants during the power generation process. According to Lutze & von Berg (2010) it is a fine powder of primarily spherical, glassy particles. The South African Bureau of Standards (SABS) defines it as a powdery residue obtained by separating the solids from the flue gases during pulverised coal combustion. It consists mainly of silica (SiO_2) and aluminium oxide (Al_2O_3) and it is obtained by electrostatic or mechanical precipitation from the flue gases of electricity generation. Improper disposal techniques of this product can lead to environmental concern by causing water and soil contamination. Fly ash is mainly used in the construction industry as an additive in concrete, road construction, agriculture, mine reclamation and other (Yao *et al.*, 2015).

1.3.2.1 Characteristics of fly ash

Fly ash is classified within two classes namely Class C and Class F with the properties for each class shown in Table 1-2 (Sutter et al., 2013). South African fly ash is typically classified as Class F with the combination of SiO_2, Al_2O_3 and Fe_2O_3 percentage being higher than 70%. The biggest difference between the two classes of fly ash is related to the percentage of CaO available in the ash. Sutter et al. (2013) presented the differences as Class C ashes being more cementitious and Class F being more pozzolanic. Class F fly ash is normally produced from burning anthracite or bituminous coal, whereas Class C fly ash is normally produced from burning lignite or subbituminous coal. Class C fly ash, in addition to having pozzolanic properties, also has some cementitious properties (Lafarge, 2016). For utilisation of Class F fly ashes within different products in the industry, cementing agents will have to be added to facilitate a reaction to gain more strength in the early setting phases.

Table 1-2 Fly Ash classes (Sutter et al., 2013).

Properties	Fly Ash Classes	
	Class F	Class C
Silicon dioxide, aluminium oxide, iron oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$), min, wt. %	70.0	50.0
Sulfur trioxide (SO_3), max, wt. %	5.0	5.0
Moisture content, max, wt. %	3.0	3.0
Loss on ignition, max, wt. %	6.0	6.0

Fly ash is usually also classified on the Loss on Ignition (LOI) and percentage of fineness (particles below 45µm). The LOI is a representation of the unburned coal remaining in the ash, which gives an indication on how well the coal is burned in the combustion process. There are three categories of South African ashes based on LOI as shown in the SANS 50450 standard, Category A with an LOI of less than 5%, Category B with an LOI between 2% and 7% and Category C with an LOI between 4% and 9%.

The ultimate strength of the fly ash will not be limited by the LOI providing that there is sufficient CaO to react with the SiO_2, Al_2O_3 and Fe_2O_3. It is crucial for Class F ashes to have a low LOI to gain more strength because of the low free CaO content (Heyns & Mostaffa

Hassan, 2014). The physical requirement of the fineness of the fly ash will play a significant role in the application in the industry. SANS 50450 categorises fly ash in two different categories as measured by the retention of fly ash on the 45µm sieve. Category N is classified as the fineness not exceeding 40% retained on the sieve and Category S where a maximum of 12% may be retained.

The most prominent oxides of elements typically found in ash includes SiO_2, Al_2O_3 and Fe_2O_3, and in lower percentages CaO, TiO_2, MgO. XRF analysis is most commonly used in South African to determine the elemental analysis of coal and ashes (van Wyk, 2015). Fly ash compounds by weight percentage for eleven Indian power stations can be seen in Table 1-3. Indian fly ashes are classified as Class F with the SiO_2, Al_2O_3 and Fe_2O_3 comprising more than 70% of the total weight percentage as described in Table 1-2.

Table 1-3 Indian Fly Ash Elemental Analysis (Chandra, 2013).

Power stations	Fly ash compounds (weight %)									
	SiO_2	**Al_2O_3**	**TiO_2**	**Fe_2O_3**	**MnO**	**MgO**	**CaO**	**K_2O**	**Na_2O_3**	**LOI**
Badarpur	57.36	31.78	1.65	4.62	0.21	0.23	0.62	0.59	0.23	2.66
Dadri	52.74	37.8	0.9	3.41	n.a.	0.24	1	0.66	0.14	3.01
Rihand	59.75	34.1	0.5	6.1	0.4	0.35	0.2	0.45	0.3	0.45
Unchahar	59.6	30.6	1.5	4.2	0.1	0.4	0.9	0.7	0.2	n.a.
Korba	62.09	31.3	1.82	3.33	n.a.	0.01	0.03	0.04	0.09	1.21
Vindhyanchal	62.89	27.08	1.1	6.12	n.a.	0.1	0.8	0.27	0.1	1.5
Ramagundam	60.83	26.63	1.13	4.19	0.08	0.8	3.03	0.9	0.4	1.81
Vijayawada	61.63	30.92	1.72	3.33	n.a.	0.05	1.11	0.61	0.13	0.4
Neyveli	38.03	43.38	1.82	4.05	0.12	0.02	7.67	0.05	0.43	3.4
Kahalgoan	60.35	30.12	1.81	5.62	n.a.	0.4	0.8	0.56	0.12	0.2
Farakka	60.3	30.9	1.2	5.02	n.a.	0.6	0.9	0.5	0.15	0.3

Van Wyk (2015) drew a comparison between studies performed on South African ashes Hattingh *et al.* (2011) and Coetzee *et al.* (2013) in his study. Van Wyk found that elemental results obtained by XRF analysis of Eskom ashes correlated very well with the study performed by Hattingh. The normalised values of three ash samples from Hattingh as obtained from van Wyk's study can be seen in Table 1-4. Evidently the sum of the SiO_2, Al_2O_3 and Fe_2O_3 are more than 70% for all three samples thus indicating Class F ashes.

Table 1-4 Normalised South African ash elemental analysis (van Wyk, 2015).

	Ash sample (weight %)		
	XA	**XB**	**XC**
SiO_2	45.2	51.3	63.3
TiO_2	1.57	1.84	1.13
Al_2O_3	24.9	25.3	23.7
Fe_2O_3	1.27	1.83	3.21
MgO	4.13	2.95	1.18
CaO	11.7	8.54	2.35
Na_2O	0.87	0.54	0.28
K_2O	0.32	0.41	1.49
P_2O_5	1.64	0.24	0.17
SO_3	4.34	4.14	2.02
MnO	4.13	2.95	1.18
Total	**100**	**100**	**100**
SiO_2 + Al_2O_3 + Fe_2O_3	**71.37**	**78.43**	**90.21**

1.3.2.2 Utilisation of fly ash

The US Environmental Protection Agency (EPA) has reviewed wide-ranging studies performed on samples of ash from different power stations, to determine the health and environmental risks posed by the utilisation of coal ash. In 2000 the US EPA determined that it was non-hazardous and proclaimed that it should be regulated accordingly (Hassett & Heebink, 2001). In India fly ash was reclassified form "hazardous industrial waste" to a waste material in 2000, and then in 2009 it was further reclassified to a useful commodity (Haleem *et al*., 2016).

Globally, the applications of fly ash within different sectors cannot account for the total volumes of fly ash available. The remainder of the unused fly ash is regarded as a waste material and disposed of in ash dams or landfill sites. More stringent environmental and disposal laws, the lack of landfill space and the ever-increasing disposal costs necessitates new recycling techniques and other uses for fly ash. In some countries fly ash is treated as a general solid waste and in others as a hazardous waste. The environmental implications of fly ash disposal include air pollution and groundwater contamination. The recycling and re-usage of fly ash is a good alternative to disposal and has environmental and economic benefits to it.

Research about fly ash in the South African sector has been done extensively over the years, with the driving force being the transformation from a waste to a product. The product solution must be of a technical and economic value in order to overcome transport costs and still be of commercial value. Different technologies were investigated in an attempt to increase the utilisation of South African fly ash. A report by Kruger & Krueger (2005) showed that the initial research of fly ash utilisation in South Africa was extensive. Sources of fly ash from different power stations were characterised in terms of their chemical, mineralogical and morphological properties. Numerous applications with potential were investigated which includes the main use in cement and concrete, soil amelioration, road stabilisation, zeolites, counteracting acid main drainage and a few other applications.

The amount of fly ash generated is directly related to the quality of coal burned. The burning of high ash coal with a low calorific value increases as the better-quality coal gets depleted. High ash coals can generate 4-10 times more ash during combustion when compared to coals with a higher calorific value (Fernandez-Turiel *et al*., 1994).

Agriculture

Soil stabilisation or solidification, usually the addition of cementitious binders to contaminated soil, has been proven to be a cost-effective solution to remediate contaminated soil (Kogbara *et al*., 2013). Studies commissioned by EPRI showed that the use of Class C fly ash in soil stabilisation in the US had no harmful effect on the environment (Hassett & Heebink, 2001). Geotechnical soil stabilisation commonly uses fly ash blended with cement as a binder. With fly ash being a CCP and much cheaper than cement, the more cement that can be replaced with fly ash for soil stabilisation, the more economical and sustainable the procedure can become (Kogbara *et al*., 2013).

Fly ash possesses qualities that can promote the chemical, physical and biological characteristics of soil. Studies shown that there is a significant potential in using fly ash to amend agricultural soils, but Ram & Masto (2010) found that it is inconclusive. The variability of fly ash characteristics, soil types and agro-climatic conditions provides inconsistent results. They found that fly ash in India are mostly alkaline and has lower levels of trace elements than some other countries. The toxic elements of concern in Indian fly ash are within the limits prescribed for the specific application, but environmental monitoring is desirable to ensure no impact on the environment.

Construction

Fly ash can be seen as a cement replacement material. Because it is a by-product from an industrial process it has economic and environmental advantages if re-used. The main use for fly ash in concrete has more to do with the enhancements to the concrete properties (Domone & Illston, 2001). The addition of cement replacement materials requires an adjustment to the water cement ratio, but this can be easily adapted if the materials are pre-blended as an extended cement. Research by Kruger & Krueger (2005) showed that all the sources of South African fly ash are high in aluminium and silica, moderate amounts of calcium and iron and low in alkalis. It was also found that the particular way in which power stations like Kendal, Matla and Lethabo produced energy, the fly ash showed very good pozzolanic characteristics. A pozzolanic material contains active silica and is not cementitious, but it will chemically react with calcium hydroxide at normal temperatures to become a cementitious compound (Domone & Illston, 2001). Research and tests confirmed that the very good pozzolanic attribute showed in the fly ash obtained from the last three fields of the array of the electrostatic precipitators enhanced the performance of concrete. The mentioned properties ensure that less water is required in the concrete mixture, which improves the density, decreases shrinkage and eases placement ((Kruger & Kreuger, 2005) & (Lutze & vom Berg, 2010)).

The ultra-fine particle distribution of fly ash can improve the physical properties of fresh and hardened concrete immensely and it is also very advantageous in the production of high-strength concrete (Domone & Illston, 2001). Mineral admixtures used in concrete to change the behaviour are also not affected by the addition of fly ash because of the low carbon content. The pozzolanic property of the fly ash also showed that if used as a cement extender it can also increase the strength of concrete in the presence of adequate moisture. The increase in strength is due to the slow rate of reaction of the fly ash in the hydration reaction, the slow reaction rate also delays the setting time (Lutze & vom Berg, 2010). A study performed for ECOBA by Lutze and vom Berg in the *Handbook on fly ash in concrete* (2010) showed that when fly ash is used in concrete, the alkalis of the fly ash and some of the cement alkalis remain bound in the hydrate phase and cannot have a damaging alkali-silica reaction. Germany uses mostly siliceous fly ash which has a very high reactive SiO_2 content and low reactive lime content as a concrete additive (Lutze & vom Berg, 2010).

One of the main requirements for building materials in Europe is the environmental and health compatibility of it. It is important to ensure that concrete products that contain fly ash may not be harmful to the environment or human health due to leaching and polluting groundwater. Lutze and vom Berg (2010) show findings obtained from leaching tests performed on concrete containing fly ash and only a very small amount of substances is released into the environment. The pore-blocking effect that fly ash has may reduce leaching of some substances if compared to concrete with no fly ash. The leachate tests performed by them showed that groundwater will not be contaminated and there are thus no limitations in using concrete containing fly ash.

Turkey's annual production of fly ash is approximately 13 million tonnes and only a small percentage of it is utilised. A study by Çiçek & Çinçin (2015) investigated the production of light weight bricks with high insulation capabilities from only fly ash and lime. Fly ash from the Seyitömer power station and slaked lime was used to manufacture the bricks. The chemical analysis of the fly ash at different size particles showed that it contained between 56% and 58% SiO_2, around 17% Al_2O_3 and 4 – 5% CaO. Real size bricks of size 200mm x 200mm x 90-110mm were manufactured containing 88% fly ash and 12% lime. It was found that the optimum conditions of steam curing in an autoclave were at a pressure of 12 kg f/cm^2 at 6 hours. The bricks produced were mechanically sound and they concluded that the bricks can be an alternative to aerated cellular concrete.

The report by Benson *et al*. (2009) for EPRI showed that the largest benefit in sustainable construction can be attributed to the use of fly ash in concrete. The substitution of cement by fly ash in the USA alone saves more than 55 trillion Btu of energy and leads to a reduction of GHG emissions by 9.6 million tonnes carbon dioxide equivalent (CO_2e).

Mine Backfilling

The extraction of coal resources leaves mining induced voids in coal rich areas that have to be rehabilitated. It will be beneficial to backfill these voids in terms of stability, safety and environmental rehabilitation. The mining industry is under pressure to manage the induced voids and to recondition the mined areas to return the land for other uses. Ashes can be used as a replacement for natural materials in structural fill to reduce the impact of mining and to assist in the rehabilitation of the area (Park *et al*., 2014).

Substantial quantities of ash are used in European countries and the USA in mining applications. The use of coal ash as a mine backfilling material is becoming an appealing option for bulk disposal. Ward *et al*. (2010) performed a comprehensive review on the beneficial applications of coal ash as a backfilling material in mining. The following specific applications of using coal ash in the mining industry were indicated in the review:

- The infilling of voids in previously abandoned or active open cast mines;
- The infilling of abandoned or active underground spaces to control ground movement or underground water flow;
- Improvement of unfavourable water quality (like acid mine drainage in mining activities);
- The use of it in roads constructed around the mine area;

- Soil stabilisation of exposed areas to prevent erosion;
- Controlling spontaneous underground combustion and
- Fertility enhancement of soil to assist in mine rehabilitation.

A substance classified as a waste has to be subjected to strict controls and regulations, notwithstanding any commercial or economical value it may have. There are two acts in the USA responsible for governing the use of fly ash in mine site applications. The first is the Resource Conservation and Recovery Act (RCRA) and the second is the Surface Mining Control and Reclamation Act (SMRCA). All power stations and mines in the US that are utilising ash in mine site reclamation are obliged to comply with the SMRCA.

Two types of backfill strategies, used in Australian, and global mines, have been identified by Sivakugan *et al*. (2006), namely, cemented and uncemented backfill. Cemented backfill materials utilises a small percentage of a cementing agent within the mixture, typically cement, or a blend of cement with other additional materials which may include CCP's. Uncemented backfilling materials has no binding agent in the material mix, which can typically be like hydraulic fills placed into voids in the form of a slurry.

Attempts for using fly ash in hydraulic mine filling technologies in Poland kept failing until the introduction of suspension technologies in the early 1980's. Hydraulic backfill technologies required a few parts of water with only one part of backfilling material, whilst the suspension technology required a range of 0.5 to 3 parts of fly ash with one part of water. The average for most applications ranged between 1.5 to 2 parts of fly ash with one part of water. After the suspension technology was introduced to fill underground mine voids, research and development projects were initiated to determine the physical, chemical and mechanical properties of the suspensions, the design and construction of installations for the suspensions, developing mining technologies for the suspensions and clarifying all the liability issues concerned with the matter (Piotrowski *et al*., 2009).

Yao *et al*. (2012) discussed some challenges that has been arising in traditional mine backfilling technologies since the early 1990's. The three traditional backfill technologies discussed in their study included rock backfill, hydraulic backfill and paste backfill. The three technologies share some drawbacks when Portland cement is used as the binding agent. These disadvantages include the cement being washed out due to high volumes of water, which may cause a decrease in strength, slurry volume loss during dewatering, that can lead to multiple filling of the same void also the long solidifying time of the backfill body, anything between 7 and 28 days, can delay the mining process. In the paste like backfill technology a silica-alumina based cementitious binder, which usually consists of fly ash, bottom ash and gypsum, is used to improve the durability of the slurry. This cementitious material uses industrial wastes as the main ingredient and a small amount of cement and the blend is then activated at a low temperature. According to Yao *et al*. (2012) this material possesses numerous advantageous and boasts good performance. The advantageous of utilising CCP's in mine backfilling technologies include economic benefits with CCP's being a more cost effective option than aggregates, the pipe technologies for the backfill are easy to design and the backfill material gains early strength that can shorten the backfilling cycle significantly.

The most renowned use of ash in non-soil mine backfilling is the utilisation of alkaline ash to treat acid mine drainage (AMD) water associated with surface and underground mines (Ward *et al*., 2014). The discharge of untreated AMD poses a serious pollution risk for ground and surface water streams. AMD is formed as a result of oxidation of pyrite in the coal spoils, when it is exposed to oxygen and water during or after the mining process. The pH value of the AMD can be as low as 2.5 and it may contain high concentrations of dissolved heavy metals and sulphates. The very acidic effluent is capable to mobilise heavy metals contained in the rock, whilst ash is highly alkaline and can act as a pH buffer and heavy metal sink when mixed with the AMD (Fytas *et al*., 1995).

Road Construction

Road construction companies have been looking for alternative materials that can be used in place of Portland cement as a low carbon binder in pavement design. Recycled concrete aggregates generated from demolition industries has gained acceptance as a stabilised pavement material. There are economic and environmental benefits to replace the cement as the binding material with fly ash. Arulrajah *et al*. (2016) found that recycled concrete aggregates stabilised with 15% fly ash is sufficient for road pavement applications. The utilisation of Class C fly ash in highway embankments proven successful in the late 1980's in the USA as shown by Glogowski (1989) and Srivastava (1989). The use of bottom ash as a replacement of fine aggregate in hot mix asphalt mixtures for road construction has been proven in Korea (Yoo *et al*., 2016).

Geopolymer concrete

The production of one tonne of cement releases approximately one tonne of CO_2 into the atmosphere (Rangan, 2008 & Assi L. *et al*., 2016). An alternative to Portland cement concrete is a sustainable geopolymer concrete that utilises waste materials instead of cement. Geopolymer concrete is produced by an alkali activation of materials rich in silica and aluminium. Fly ash is the source material of choice mostly due to its low cost and ample availability (Pavithra *et al*., 2016). The alkaline activation liquids are mostly from soluble alkali metals that are typically sodium or potassium based (Rangan, 2008). Fly ash based geopolymer concrete will typically consist of fly ash, an activating solution such as sodium hydroxide or more commonly sodium silicate, water and aggregates (Assi L. *et al*, 2016). Low calcium, Class F, fly ash is the preferred source material. The silicon and aluminium oxides in the Class F fly ash reacts with the alkaline solution to form a paste. The geopolymer paste binds the aggregates and unreacted materials to form geopolymer concrete. The higher calcium presence in Class C fly ash can possibly interfere with the polymerization process (Rangan, 2008).

Several studies on the Class F geopolymer concrete with 100% fly ash (no cement) has shown very favourable results, like a substantial increase in resistance in acid and sulfate attack, high early compressive strength and satisfactory performance under higher temperatures (Rangan, 2008 & Assi L. *et al*., 2016). The mentioned results show huge potential in developing these methods further as an alternative to cement based concrete. The application of it may possibly be limited, for the near future, to only precast concrete applications due to the heat required during the curing process (Assi L.N. *et al*., 2016).

Other uses

A study in China performed in 2015 showed that the application of FGD gypsum and fly ash in fire resistant panels can be a promising future application of these CCP's. Li, J. *et al.* (2015) tested the physical, mechanical and insulating properties of panels manufactured from FGD gypsum and fly ash and compared the results to panels manufactured from commercial gypsum and fly ash. The biggest difference between the FGD and commercial gypsum panels was the insulation capability. The panels manufactured from FGD gypsum and fly ash showed higher insulation capabilities and sufficient mechanical capabilities.

1.3.3 Low cost housing

There are different sources of air pollution in South Africa, with Eskom being one of the biggest contributors of air pollutants, but domestic burning has by far the biggest impact on human health. Informal settlements in South Africa are dependent on burning fuels like coal, biomass or paraffin for cooking and space heating. The emissions released from burning for these purposes causes damaging effects on human health. Studies have shown that the pollution levels are 2-3 times higher in summer and up to 6-7 times higher in winter than the accepted ambient air quality standards (Van Niekerk, 2006). The burning of low energy content fuels results in very high indoor exposure to particulate matter.

A large group of the South African population resides in low cost housing in informal settlements. These low cost houses are mostly constructed from corrugated iron; this material is chosen due to the availability and ease of constructability. The dwellings within these informal settlements have been found to have almost no thermal efficiency and this leads to large amounts of income spent on space heating in winter. Houses are constructed without ceilings or other forms of insulation to keep the costs as low as possible. "*The people who can least afford it have to pay the highest percentage of their earning to make their lodgings habitable*" (Mathews *et al*., 1995). Inefficient heating methods are still primarily used in these communities and by using low energy fuels the exposure to particulate matter is aggravated within these houses (Mathews & van Wyk, 1996).

Numerous attempts have been made since the 1960's to alleviate informal settlements of air pollution and to improve the health of the human population and the environment (van Niekerk, 2006). The initial efforts to reduce pollution included burning devolatilised coal, using low smoke stoves and fuels and electrification. A study by van Niekerk and Swanepoel (2002) on the impact of electrification found that electricity does not satisfy all needs, and especially in informal settlements it has no effect on the coal usage. Social and cultural factors within the communities in low income settlements have a big influence on the decision to utilise coal. One initiative to clean up the air that has had some success is the eMbalenhle Air Quality Project (MAQ) which is also referred to as the Basa Magogo project, which is an adapted way of lighting a fire within a drum. This alternative lighting method saved the communities in coal consumption; it eliminates most of the smoke, as formed in a traditional imbaula stove, and it is a cost effective alternative. Community acceptance of alternative methods instead of traditional ways seems to inhibit this process of becoming completely successful (Van Niekerk, 2006).

Space heating requires the burning of high volumes of wood and/or coal, especially during winter. Coal is typically chosen as burning material due to the low price and it produces extended heat release. Several researchers, including Mathews & van Wyk (1996) and van Niekerk (2006), found that by increasing the thermal efficiency of these houses in the informal settlements it can address not only the indoor pollution and associated health risks, but also the exhaustion of the natural wood and coal resources. According to Mathews *et al.* (1995) it can be seen as an improvement to living conditions but not a final solution to the problem. Different scenarios were tested and simulated by Mathews *et al.* (1995) to gather information on ways of improving the thermal efficiency of existing homes within these settlements. It was found that the most effective way would be to modify these existing homes with inexpensive materials. An effective method to conserve energy within these homes is to provide thermal insulation for the walls and roofs. By doing this it will inhibit major losses of thermal energy through the houses in extreme temperatures, and it will ensure more heat contained inside in the winter. Their studies found that the installation of ceilings in more formal type houses (RDP houses) can contribute to an energy saving of up to 74% in winter times.

Housing is a global problem, especially in developing countries. Statistics in 1995 in South Africa showed that 1300 new houses had to be built every day in order to relieve the housing crisis (Mathews *et al*. 1995). Unfortunately, the residents of informal settlements in South Africa have to address the situation themselves by constructing ultra-low cost housing with light weight building material, which mostly includes corrugated iron sheets. The nature of these structures lend itself to provide basic protection against the elements, but it is extremely thermal and energy insufficient. By improving the thermal and energy efficiency of these housing structures it can address pollution problems, the exhaustion of our natural resources and also human health risks.

1.4 SUMMARY

The utilisation of CCP's in sustainable construction can a lead to a reduction of energy and water use, this is due to the reduction of emissions and resources required for transformation of natural resources. Fly ash is the fine fraction carried out of the boiler by the flue gas and FGD gypsum is the product of the glue gas desulphurisation system.

Natural gypsum ($CaSO_4 \bullet 2H_2O$) is a hydrous calcium sulphate and FGD gypsum is usually termed as synthetic gypsum, due to its production within WFGD scrubbing systems. FGD gypsum is the largest contributor to the synthetic gypsum market worldwide, and it is freely substituted for natural gypsum due to its similarities in chemical composition. Dissimilarities exist between natural and FGD gypsum. FGD gypsum has a finer grain size and a higher moisture content which can influence handling and transportation. The finer grain size will result in less grinding before utilisation in manufacturing processes. FGD gypsum has a smaller amount of impurities compared to natural gypsum.

FGD gypsum is ever more replacing natural gypsum in the wallboard industry. The replacement of natural gypsum with FGD gypsum can ensure the conservation of the natural resource. By increasing the utilisation, costs and area required for landfill can be avoided. The use of FGD gypsum in agriculture is very promising and it can act as a soil amendment for certain soil types. FGD gypsum can neutralise acidic soil conditions and in return generate higher crop yields. FGD gypsum is used as an additive to cement to act as a retarder and enhance grinding characteristics of the clinker. Saline soil conditions of reclaimed tidal lands can be remediated with FGD gypsum. Fire resistant panels manufactured from 100% FGD material showed promising results. The mechanical strength was not as high as commercial gypsum products, it was not water resistant but it showed higher insulation capabilities and no detrimental environmental harm.

The chemical and physical characteristics of FGD gypsum will determine the sector that it can be used in. FGD gypsum quality can be determined with VGB Powertech standard specifically developed for FGD gypsum.

Fly ash consists mainly of silica (SiO_2) and aluminium (Al_2O_3) and it is obtained by electrostatic or mechanical precipitation from the flue gases of electricity generation. It is classified in Class C and Class F, with Class C being more cementitious due to a higher CaO content and Class F being more pozzolanic. The combustion of bituminous coal sources will provide Class F fly ash. The applications of fly ash within different sectors cannot account for the total volumes of fly ash available. Fly ash disposal can cause environmental harm by air and groundwater pollution, thus the recycling and re-use of the material can pose environmental and economic benefits.

The utilisation of fly ash in agriculture as a soil stabilisation can be advantageous, the more cement that can be replaced with fly ash in the application, the more economical and sustainable the procedure can be. Fly ash is a cement extender, and by replacing a portion of the cement with ash will improve the density and durability, decrease shrinkage and ease placement. Fly ash can improve the physical properties of concrete and can produce high-strength concrete. Light weight bricks with high insulation capabilities can be manufactured from a fly ash and lime mixture. The substitution of cement by fly ash in the USA only, saves more than 55 trillion Btu of energy and leads to a reduction of GHG emissions by 9.6 million tonnes CO_2e.

Ash can be used as a replacement material for natural materials to fill mining voids and to provide structural fill and rehabilitate the mined area. Alkaline ash can be utilised to treat and neutralise acid mine drainage (AMD) water associated with surface and underground mines. Ash can be utilised in road construction as a replacement for cement as the binding material. Geopolymer concrete is produced from materials rich in silica and aluminium. Class F fly ash is typically used along with an activating solution, water and aggregates to produce geopolymer concrete without any cement. Geopolymer concrete showed huge potential, especially in the precast concrete industry. FGD gypsum and fly ash can be used together in the production of fire resistant panels with an increased insulation, mechanical strength and water resistant capability, which can possibly be utilised in low income communities as a form of insulation.

The availability of fly ash is more abundant and it has also been accessible as a sustainable material much longer than FGD gypsum. More research has been performed on the utilisation of fly ash and it evident in the amount of possibilities for utilisation available compared with the FGD gypsum. International uses and best practises for both FGD gypsum and fly ash will be discussed in this dissertation.

2. INTERNATIONAL BEST PRACTISE AND UTILISATION

2.1 INTRODUCTION

The international best practises and utilisation of FGD gypsum and fly ash are implemented in the United States, European Union and China. Poland will also be discussed as a country with a very well established CCP management system. Fly ash utilisation in Australia and India will be significant to the study.

2.2 FGD GYPSUM

2.2.1 United States

The American Coal Ash Association (ACAA) preserves statistics on the utilisation of FGD gypsum in the US, with 2013 being the latest year available on record. There were 24.4 million metric tonnes of FGD gypsum produced in the US, and 11.9 million tonnes of this were utilised. The primary sector of consumption was the wallboard industry with almost 7.5 million tonnes used. Prefabricated gypsum wallboard dominates the use of FGD gypsum in the US with over 63% accounted to this industry. Other industry uses include gypsum used in structural fill, mining applications, feed for clinker and agriculture as shown in Figure 2-1 as adapted from ACAA.

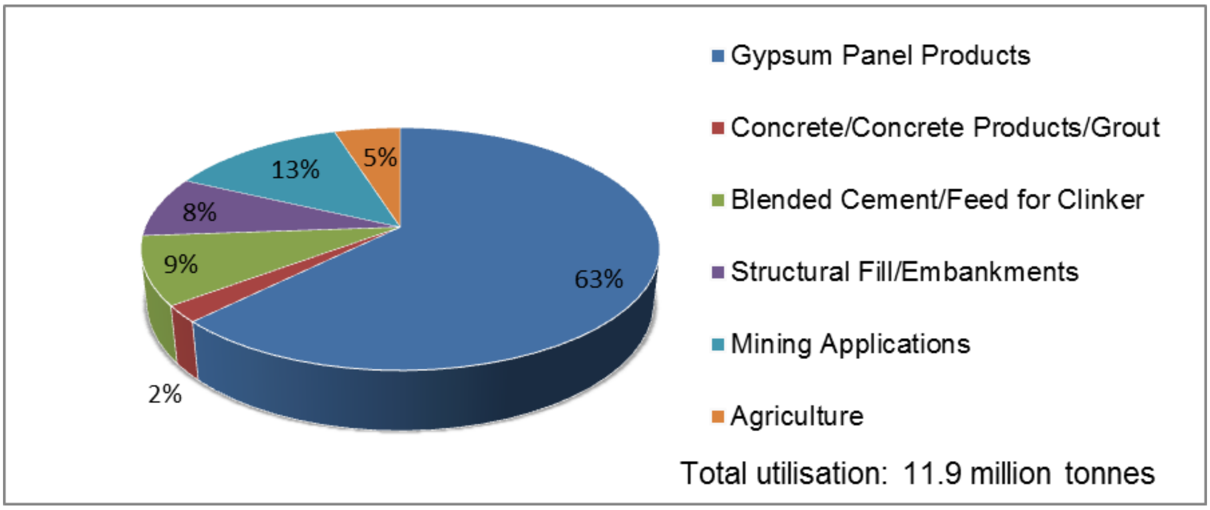


Figure 2-1 FGD gypsum utilisation in USA in 2013 (ACAA, 2015).

Gypsum derived products, which includes wallboard, Portland cement, plaster products, agricultural uses and others, totalled 14.1 Mt. The total amount was produced at a value of 3.01 billion dollars in 2013. These gypsum products had an increase in production of 12% and a corresponding increase in value of 30% compared to the previous year, as can be seen in Table 2-1. The large increase in price is mainly due to the increase in the price of prefabricated products in the US (USGS, 2015).

Table 2-1 Gypsum products sold or used in USA (USGS, 2015).

GYPSUM PRODUCTS (MADE FROM DOMESTIC, IMPORTED, AND SYNTHETIC GYPSUM) SOLD OR USED IN THE UNITED STATES, BY USE[1]								
(Thousand metric tons and thousand dollars)								
		2012				**2013**		
Use		**Quantity**		**Value**		**Quantity**		**Value**
Uncalcined:								
Portland cement		1,040		19,200		875		18,000
Agriculture and miscellaneous[2]		519		23,300		569		22,900
Total		1,560		42,500		1,440		40,900
Calcined:								
Plasters		75		32,000		79		34,000
Prefabricated products[3]		10,900		2,230,000		12,600		2,940,000
Total		11,000		2,270,000		12,600		2,970,000
Grand total[3]		12,500		2,310,000		14,100		3,010,000
[1]Data are rounded to no more than three significant digits; may not add to totals shown.								
[2]Includes synthetic gypsum.								
[3]Includes weight of paper, metal, or other materials and some synthetic gypsum.								

In the US, the dominant amount of gypsum used in products is calcined gypsum. Natural and synthetic gypsum are delivered to calcination plants in the US for processing and subsequently it is used in a diversity of products.

The principal source of synthetic gypsum in the US was FGD gypsum from coal fired power stations, with smaller quantities also derived from chemical processes. Many of these coal burning power stations are required to have sulphur dioxide scrubbing systems installed, which created a substantial amount of synthetic gypsum that could be acquired at a better cost than natural mined gypsum. This in turn led to numerous wallboard manufacturing facilities in close proximity to these power stations (USGS, 2013). The USGS stated that projected sales of synthetic gypsum in the US in 2013 decreased by 11% to 10.8Mt compared to the previous year, and that 51% of synthetic gypsum produced in 2013 was land filled. The 10.8Mt of synthetic gypsum was produced by 16 different companies and the value linked to this sale was around 17.9 million dollars. Synthetic sources of gypsum were responsible for approximately 66% of the gypsum mined or produced in the US in 2013, which was a 10% decrease in relation to 2012 (USGS, 2015). The lower costs associated with the transportation of FGD gypsum due to its location in close proximity to wallboard manufacturing facilities, ensured that synthetic gypsum played a substantial role in the gypsum marketplace.

Uncalcined gypsum was mostly used in Portland cement production and agriculture, and calcined gypsum is used in the wallboard manufacturing industry. In 2013 there were roughly 2.03 billion square meters of wallboard products shipped in the US. A 15% increase was noted from the previous year (USGS, 2015). A key economic indicator used in the US by the wallboard and gypsum industries is the issuance of new building permits because the residential housing market is accountable for almost 60% of the gypsum consumption. In the future natural gas will compete within the coal fired electricity generation industry, which means that the production of synthetic gypsum will decrease in the US (USGS, 2015).

In 2014 the housing and construction industry markets increased in activity in the US compared to the previous year. This resulted in a 5% upsurge in gypsum production and a 5% increase in apparent consumption (USGS, 2015).

Recycled gypsum in the US, mainly from the wallboard and demolition industries, was used in the agricultural industry and as raw material to manufacture new wallboard. Alternative markets for recycled gypsum in the US potentially included field marking on athletic tracks, stucco additives in cement production, grease absorption, drying of sludge and in the treatment of water (USGS, 2015).

Wallboard that was not recycled would often be disposed in municipal landfill sites or construction and demolition landfill sites. It is concerning that wallboard, manufactured from natural or synthetic gypsum, can possibly lead to the production of hydrogen sulphide gas under wet, anaerobic conditions that might exist in these landfill sites. Similar conditions could also lead to the release of organomercury species (Ladwig, 2006).

2.2.2 European Union

Since the early 1980's FGD systems has been implemented in Europe. The gypsum industry and the electricity industries partnered to create the best practices to convert the SO_2 present in the flue gas to a valuable end product. The use of FGD gypsum in the EU15 countries relies heavily on the construction and wallboard industry. The EU15 countries comprises of the following fifteen countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and the United Kingdom. The utilisation of FGD gypsum within each sector in Europe as adapted from the ECOBA figures can be seen in Figure 2-2. A total of 10.3 million tonnes of FGD gypsum was produced in the 2010 year with a utilisation of just over 8 million tonnes, this equates to a utilisation rate of 78%. High strength gypsum blocks accounted for 2.3% of gypsum utilisation in the European Union (EU) in 2003. In 2006 this market has not yet been developed in the US. If the magnesium and soluble salt levels are kept low enough, FGD gypsum is a very good material to be used in these blocks (Ladwig, 2006).

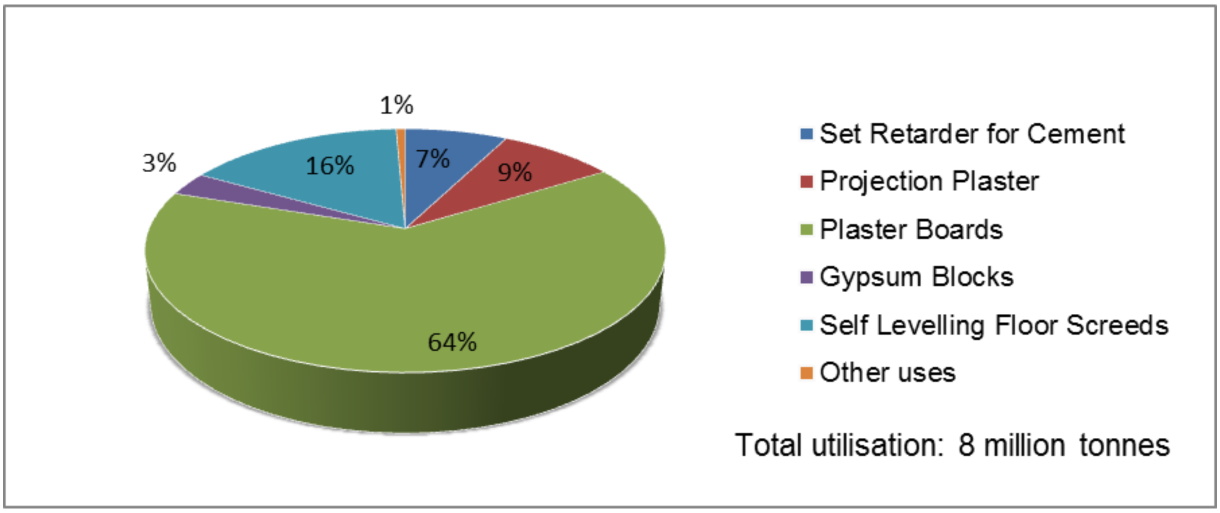


Figure 2-2 FGD gypsum utilisation in the EU15 countries in 2010 (ECOBA, 2015).

If a specific set of quality criteria is met, as shown in Table 2-2, the FGD gypsum derived from the FGD process is classified as a product and not a waste, as set out in the EU Directive and presented in Figure 2-3.

Table 2-2 Eurogypsum quality criteria for FGD gypsum product (Eurogypsum, 2005).

EUROGYPSUM Quality criteria for the product FGD Gypsum			
Quality Parameters	**Expressed as:**	**Unit**	**Quality Criteria**
Free Moisture	H_2O	% by Weight	< 10
Calcium sulphate dihydrate	$CaSO_4$ x $2H_2O$	% by Weight	> 95
Magnesium salts, water soluble	MgO	% by Weight	< 0.10
Sodium salts, water soluble	Na2O	% by Weight	< 0.06
Chloride	Cl	% by Weight	< 0.01
Calcium sulphite hemihydrate	$0.5H_20$ x $CaSO_3$	% by Weight	< 0.50
pH			5 - 9
Colour	Ry = L*a*b	%	white
Odour			neutral
Toxicity			Non toxic

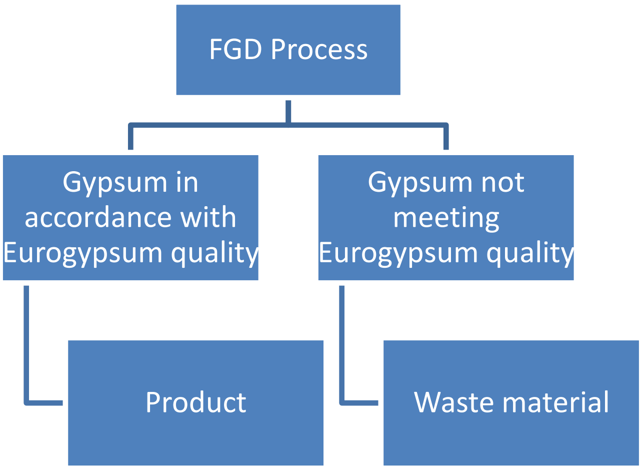


Figure 2-3 Classification of FGD Gypsum in Europe (EU Directive, 2008).

In Europe the FGD gypsum is used in the construction industry, mining industry (mainly in the form of binders and fillers), and also largely in the agricultural sector. FGD gypsum produced in power plants has made a raw material available and this material is near identical to natural gypsum in both specifications and quality.

2.2.3 China

The Chinese wallboard industry was established later than developed countries. It advanced rapidly and wallboard is now the preferred construction material for non-loading bearing walls and ceilings in China (Global gypsum, 2011). The Beijing New Building Materials Company Ltd (BNBM) was established in 1979, revolutionising the large-scale manufacturing of gypsum wallboard in China. The escalation happened at the end of 2007 when policies were put in place by the Government to limit the use of hollow and clay bricks, and to encourage the use of gypsum wallboard. In 2009 BNBM owned 40% of the market share in gypsum wallboard manufacturing in China. It was forecasted that BNBM will reach a capacity of 1.5 BNm^2/annum in 2012, thus becoming the largest gypsum wallboard producer in the world.

Asia showed a growth in the use of wallboard. Together with new gypsum plants, the increased production of gypsum ensured China to be the world leading supplier of gypsum. The gypsum demand in China is mostly influenced by the strength of the construction industry and the demand in the real estate industry.

2.2.4 Poland

The WFGD system in Poland utilises limestone as the scrubbing material in the process. The selection of the limestone is the most important factor in determining the quality of the end product of FGD gypsum. The porosity, purity, hardness and particle size distribution are all very important specifications to consider when the limestone is chosen. There are currently around 2.1 million tonnes of FGD gypsum available annually in Poland. When full capacity of the system within the country is achieved the availability will rise to around 4.5 million tonnes annually (EDF Ekoserwis, 2016).

The FGD gypsum obtained from the power stations are not dried, it is just drained and collected from the drying belts. When FGD gypsum dries it creates a glaze around each particle and it closes the pores. The FGD gypsum product (as determined by Eurogypsum quality parameters) is transported from the power station and stored in a large tented warehouse at a CCP management company. The FGD gypsum product can be loaded directly onto trucks for use in the cement and construction industry; alternatively it is packed into big bags for agricultural applications. Dried gypsum cannot be used in agriculture, it can however be used in the wallboard construction and brick making industry.

2.3 FLY ASH

2.3.1 United States

The ACAA releases an annual *CCP's Production and Use Survey* report which shows the generation and utilisation of fly ash and other CCP's. According to this report the US produced 53.4 million tonnes of fly ash in 2013 and utilised 23.3 million tonnes, which is a utilisation rate of around 44%. The percentage of total utilisation of fly ash within different sectors in the US as adapted from ACAA can be seen in Figure 2-4.

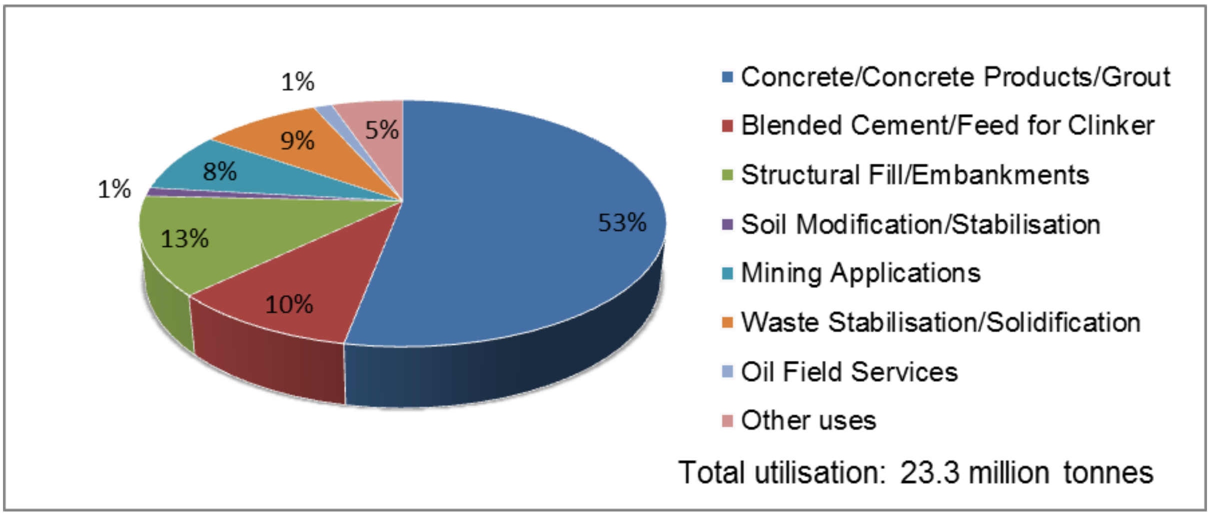


Figure 2-4 Fly ash utilisation 2013 in USA (ACAA, 2015).

In 2001 Vorries provided results where CCP's, specifically coal ash, were replaced back into the mining area where it originated from. Vorries (2001) showed that he researched the replacement of materials back into the mined area extensively. Furthermore, the research indicated that the placement typically resulted in a positive impact on the environment because it alleviated potential mining hazards. According to Vorries (2001), the beneficial uses of the placement of CCP's back into the mined areas included the following:

- the prevention of acid mine drainage formation;
- soil amelioration for abandoned mine lands;
- construction material for dams where needed as a compact base and
- a non-toxic fill material for fill area in final placement.

In contrast to the study performed by Vorries (2001), Stant (2007) specified that there is a growing concern regarding the placement of coal combustion wastes in active and abandoned coal mines in the Pennsylvania area. The main concern is the contamination of ground- and surface water with toxic elements or heavy metals above threshold concentration limits. Alarms was raised regarding the uncertainties that CCP contamination may result in an even worse water quality compared to the already bad conditions created by the formation of acid mine drainage. The monitoring data at fifteen mining sites of ground- and surface water were examined during to confirm or oppose the safe use of CCP's in mining fills. Some of the findings included:

- the monitoring data indicated that CCP contaminated water sources at 10 of the 15 coal ash mine fill sites;
- waste and site characterisation is not sufficient before placement of CCP's in mining areas to avoid the placement of materials with leaching capabilities in these areas;
- surface water and groundwater quality monitoring should happen more frequently to identify possible negative impacts early on and
- the promotion of safe uses for CCP's instead of mine filling should be prioritised.

A study performed by Koehler (2002) observed the use of CCP's as a structural fill in specific selected areas at the Trapper Mine in Colarado, USA. CCP's, which also included FGD material, have been used as a backfill material since the early 1980's. Five hundred thousand tonnes of CCP's were tested annually and afterwards applied to fill voids in the mine. The tests included the determination of physical and chemical characteristics as well as the leaching of the CCP's. A groundwater monitoring network was put in place to guarantee that the quality of the water was not affected with the placement of CCP's in the voids. Koehler's study (2002) concluded that it was unlikely that the placement of the CCP's in the voids would have any adverse impact on the water quality, due to the low permeability of the CCP's and the low infiltration rate of the mine water into the voids.

2.3.2 European Union

In the European Union fly ash is recognised as a non-hazardous substance unless it or its leachate contains toxic substances at a concentration that can demonstrate hazardous characteristics. The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) was adopted in 2006 by all EU countries. The REACH regulation stipulates that comprehensive information is required regarding the toxicology and ecotoxicology of all substances used in industries and even homes. The REACH regulations were introduced in EU to improve the protection of the environment and human health from risks posed by chemicals. The risks linked to substances must be identified and managed by companies for their products available on the market. If the risk of a specific substance is unmanageable it will be classified as a hazardous waste (European Chemical Agency, 2016).

Similarly to the report released annually by AQAA, the European Coal Ash Society (ECOBA) releases production and utilisation data for CCP's in the EU15 countries. The latest full set of data available is for 2010 and it shows that within these fifteen countries a total amount of 31.6 million tonnes of fly ash was produced and 13.8 million of it was utilised within different sectors. This gives a total utilisation rate of fly ash within Europe of 43%. The percentage utilisation of fly ash within the different regions can be seen in Figure 2-5 as adapted from ECOBA.

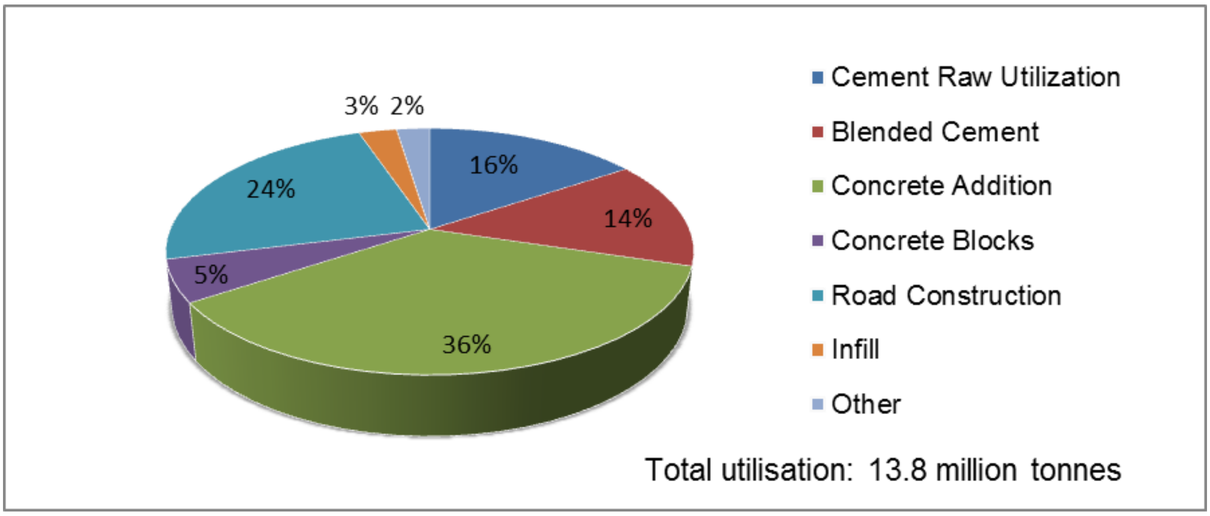


Figure 2-5 Fly ash utilisation in Europa in 2010 (ECOBA, 2015).

The Union of the Electric Industry – EURELECTRIC released a report in 1999 to address the issue that fly ash is concerned a hazardous waste. In the United Kingdom coal fly ash is a controlled waste and the disposal of it is regulated under the 1994 Waste Management Licensing Regulations. The United Kingdom falls under the banner of the EU, but the information pertaining hereafter can give a more in depth summary of inter country usage. Fly ash is classified as an inactive waste in the Landfill Tax presented in the UK in 1994, thus attracting a lower tax compared to other wastes. Coal fly ash is also not listed as a hazardous waste in the 1996 Special Waste Regulations.

The report by EURELECTRIC also states that fly ash has shown no toxic properties or negative impact on the environment or human health, and also that they are convinced that fly ash should be listed as a non-hazardous waste. The UK promotes the use of fly ash in construction products to reduce the effect of greenhouse gases. The United Kingdom Quality Ash Association (UKQAA) releases annual statistics on coal ash products. Figure 2-6 shows the coal ash utilisation in the UK in 2011, and the usage is positioned in the building and construction industry.

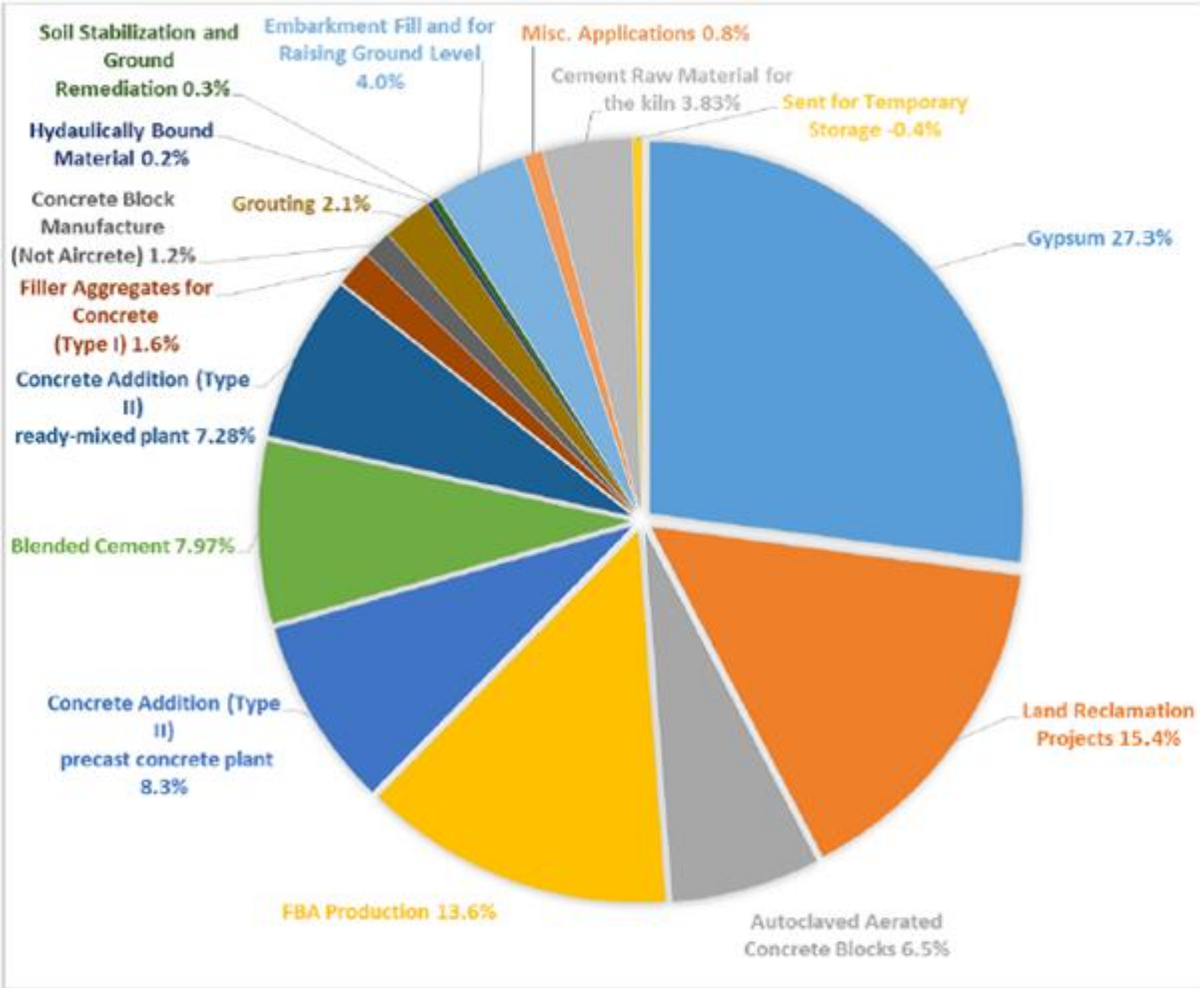


Figure 2-6 UK coal ash utilisation data for 2011 (UKQAA, 2015).

2.3.3 China

China generated 540 million tonnes of fly ash in 2011 with a utilisation of 367 million tonnes, a very high utilisation rate of almost 68% (Yao *et al*., 2015). The cement industry utilised 41% of the fly ash, the bricks and tiles industry 26%, concrete 19% and the others as shown in Figure 2-7, as adapted from Yao *et al*. (2015). A small region in the Northern part of China produces fly ash with very high alumina content but most fly ash in China can be classified as Class F ashes (Shuhua *et al*., 2016).

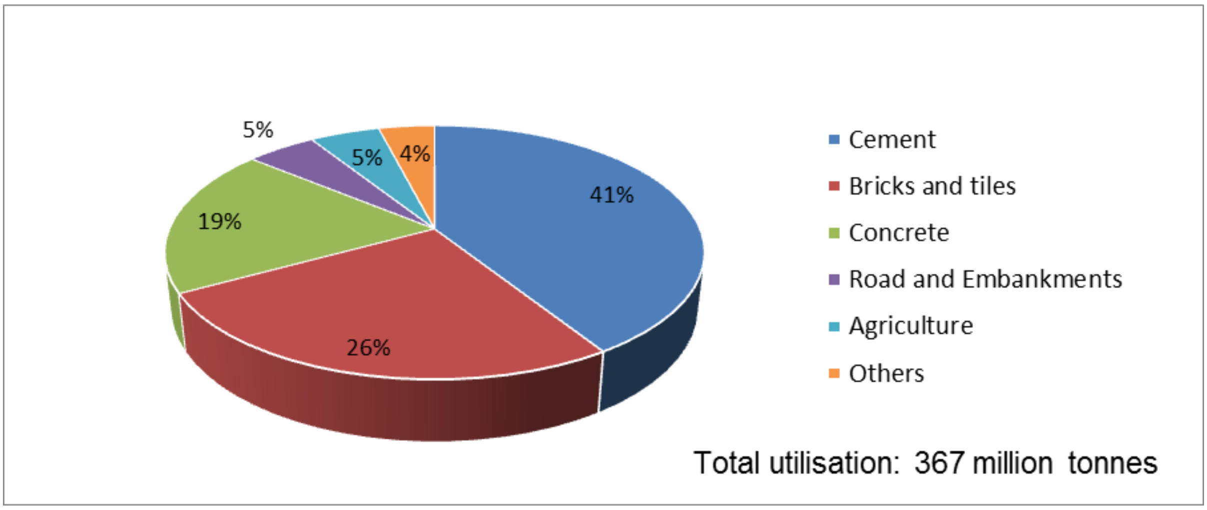


Figure 2-7 Fly ash utilisation in China in 2011 (Yao et al., 2015).

2.3.4 Poland

A mixture of fly ash, cement and water was introduced in 1967 as a compaction grout for areas where roof stability in underground mines was required. Since the introduction of this mixture it has had a very positive impact in the Polish mining industry. The Polish mining industry has been using mining waste materials, sand and CCP's to fill mining voids and to provide support structure in underground mines. Benefits included the role of a fire retarder that prohibited most of the spontaneous combustion in the underground void areas. By producing cavity longwalls, thus grouting the void area with this mixture, it also assisted in improving the ventilation and a reduction of heat loads. It was found that mine backfilling will deliver the best results in terms of structural support and environmental benefits when the chosen void filling technology is performed as soon as possible after mineral extraction (Palarski, 2000).

2.3.5 Australia

The Ash Development Association of Australia released their annual survey results for 2014 in their November 2015 issue of Ash Matters bi-annual publication. The report showed that Australia generated almost 11 million tonnes of fly ash in the 2014 year. It is documented that 5.4 million tonnes of the produced fly ash were made use of in the country, which gives a utilisation rate of 48%. A volume of 2.2 million tonnes were utilised in internal projects, like haul roads and onsite remediation. These projects do not generate an income but it is documented as cost avoidance. The total documented fly ash sales in Australia in 2014 amounted to 2.14 million tonnes, with the cement and concrete industry utilising 80% of the fly ash. The mining industry utilised 0.15 million tonnes of fly ash or 7%. The sectors utilising ash can be seen in Figure 2-8 as adapted from the ADAA data. The difference of 1 million tonnes of fly ash can be attributed to other uses with no income.

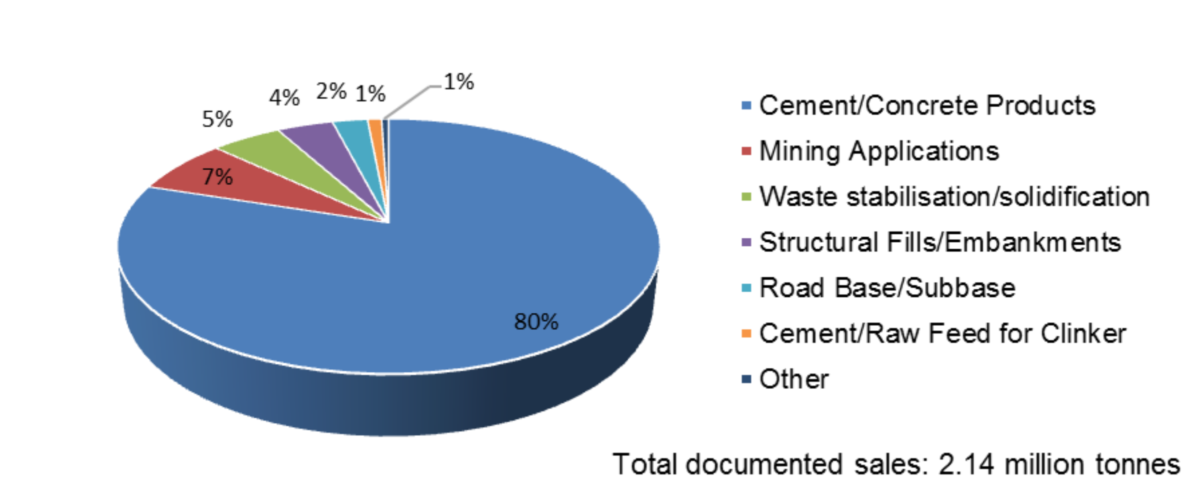


Figure 2-8 Australian fly ash sold in 2014 (ADAA, 2015).

Ward *et al*. (2014) indicated that there are numerous mine rehabilitation projects where CCP's are used to fill voids in open cast mines in Australia. Several Australian examples mentioned in the Coal Combustion Products Handbook by Ward *et al*. (2014) are all very successful projects. Examples of these projects include:

- A rehabilitation project where the fly ash from the Bayswater power station is used to fill voids in an adjacent opencast mine. Layers of ash and topsoil were used to fill the voids and lastly covered with topsoil and re-vegetated. The topsoil mixture used during the project also included ash and by products from other industrial activities in the area. This project was so successful that the land may be returned to grazing in the near future.
- Ash from the Millmerran power station is also placed into voids at an open cast mine nearby. Techniques have been developed to effectively place the ash by minimising dust and preventing water ingress.

Three power stations with each their own opencast coal mine in the Victoria state are all practising the placement of ash in voids, but each in their own manner. Ash from the Yallourn power station is dried in ponds and then placed in old mine voids as approved by the EPA.

The ash produced from the Hazelwood station has a very high magnesium content and is placed in a specially prepared area in the open cut to facilitate future use as a magnesium ore. The fly ash from the Loy Yang mining complex is deposited in a drying pond, and once dried the leached ash is then moved to a dry disposal area in the mine for final placement.

There are a few success stories of using coal ash in Australia for mining applications, but the uses within this sector is still limited (Park *et al*., 2014). Public concerns regarding the contamination of scarce water resources in Australia have prevented many projects in Australia where ash could have been utilised within the mining industry. As a precaution against ground- and surface water contamination all process materials and also the receiving environment needs extensive characterisation in Australia. This is similar to leaching tests performed in South Africa as recommended by the DEA.

The disposal of ash in Australia is regulated by their Environmental Protection Agency (EPA) whilst mining rehabilitation is controlled by the Department of Mining. The current practice for using ash in mining applications is based on a case per case scenario per power station, where the power generator has to seek approval. However, the disposal of power station ash in mining applications is not a common practice in Australia. The best time to initiate the approval process for utilisation of ash in mining applications will be during the initial approval award for the mining process. The EPA's in Australia will generally be in favour of co-disposal within the mining facilities because it will reduce land use for disposal (Park *et al*., 2014). Issues that will have to be addressed within this process will be the noise and dust generated during the transportation of ash. In Australia the environmental liability shifts towards the mine when the ash is used within the rehabilitation process. If no proper incentives are in place the mine does not want to take this responsibility and there are typically less issues in situations where the power station and mine have a joint owner. The main concern of environmental liability is the contamination of surface water and aquifers. The placement of ash in ponds to ensure the ceasing of leaching can be performed before disposing of it in mines.

As of 2016 there is no statutory requirement in Australia for FGD installations at power stations. No FGD gypsum has been produced yet. In New South Wales, Australia, the demand for gypsum in the cotton and canola farming industry is increasing. Gypsum is used as a soil conditioner in these specific farming industries, where cotton and canola requires three times more gypsum as the wheat industry. The possibility of replacing natural mined gypsum with FGD gypsum does exist (Sullivan & Dufour, 2010).

2.3.6 India

The Central Electricity Authority (CEA) in India has been monitoring the generation and utilisation of fly ash since 1996. Indian coal is of a low grade and has a very high ash content of around 30 – 45%. The high ash content of coal used within the power generation industry in India results in large volumes of fly ash that has to be disposed of in an environmentally safe manner.

The Ministry of Environment, Forests and Climate Change in India has released several notifications in the Indian Government Gazette on fly ash utilisation, in order to reduce land requirements for disposal and simultaneously address pollution. The first notification was released in September 1999 and the latest amended notification dated November 2009. The regulations addressed in these notifications include the use of fly ash in construction, the utilisation of fly ash at each of the power stations in India and also some specifications on the use of ash based products. The regulations states, among other things, that every construction company involved in building activities within a 100km radius of a coal generated power station shall use only fly ash based products for construction.

Furthermore, it states that every coal based power plant shall make ash available for a lengthy period, at no cost or consideration, for the purpose of manufacturing ash-based products for construction activity. Regulations provided in the notification in 2009 states that all existing power plants has to reach a fly ash utilisation rate of 100% within five years and new plants must reach it within four years from publication date. As a result of the notifications released and enforced the utilisation rate of fly ash increased from a mere 1 million tonnes/annum before the intervention to 45 million tonnes/annum in 2005 (Kumar et al., 2005). The annual CEA report showed that India produced around 184 million tonnes of fly ash between April 2014 and March 2015 with a utilisation of around 102.5 million tonnes, which gives a utilisation rate of 55.7%. The summary of the data collected in this period from 145 power utilities in India can be seen in Table 2-3 (as adapted from the CEA report). Fly ash in India is used in the construction industry, cement, road construction and agricultural value products, but none of these sectors can substantially utilise the vast amounts of ash produced.

Table 2-3 Fly ash generation and utilisation in 2014/2015 in India (CEA, 2015).

Description	Year 2014-2015
Number of Thermal power stations from which data was received	145
Installed capacity (MW)	138 915.80
Coal consumed (Million tonnes)	549.72
Fly ash generation (Million tonnes)	184.14
Fly ash utilisation (Million tonnes)	102.54
Percentage utilisation	55.69
Average ash content (wt. %)	33.50

The main sectors that incorporate fly ash in India can be seen in Figure 2-9, as adapted from the CEA report. The one sector not included in the figure is the hydro power sector, which accounts for a usage of around 0.01%. The majority of sectors utilising coal fly ash forms part of the construction industry.

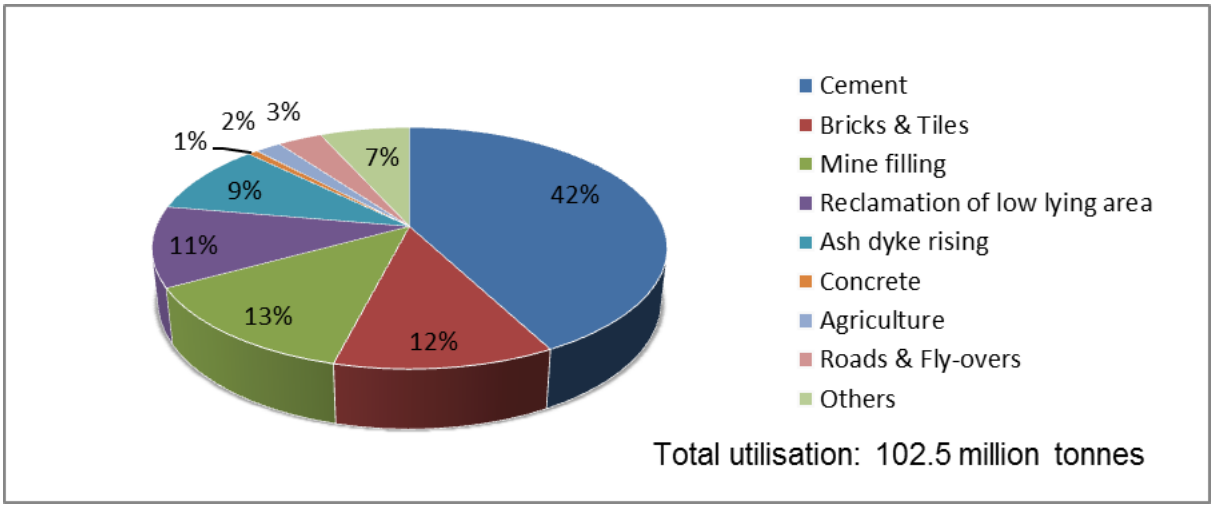


Figure 2-9 - Fly ash utilisation in India in 2014/2015 (CEA, 2015).

Dutta & Sarkar (2016) indicated in a report that sand is currently being used in India as a mine backfill material. Sand is also a very valuable material in the construction industry and it plays an integral part in developing new infrastructure. The large amounts of fly ash produced and available can act as a replacement material for sand, and subsequently be used in bulk volumes. This solution will have a twofold purpose, one being the conserving of sand for future infrastructure development and secondly in reducing ash disposal by landfill. The proposed method of mine backfilling in India with ash utilisation is the High Concentration Slurry Disposal (HCSD) method. The main components of the technology are mixing the slurry (in the form of a paste) on site and then pumping it into the underground voids. Dutta & Sarkar (2016) stated that the paste backfill technology utilising coal ash has numerous advantages over traditional hydraulic backfill technologies.

2.4 SUMMARY

The production of gypsum wallboard is expected to increase as more nations show interest in the utilisation of it in their construction industries. As the design of wallboard manufacturing plants change to accommodate FGD gypsum, less gypsum will be mined. FGD gypsum is successfully used as a replacement material for natural gypsum in the cement and agriculture industries. The acceptance of FGD gypsum as a direct substitute in European countries conserves the natural resources and secures the future of supply. The situation is similar for the United States and China.

Early research shows that the use of fly ash in concrete has always been the single biggest end user. This is still evident in the usage data provided by AQAA and ECOBA where the concrete and cement industries account for almost two thirds of the total utilisation in these countries. The construction sector has predominantly used fly ash, especially as a cement extender in concrete and as an additive in blended cement. Other areas of use for fly ashes includes the road construction and agriculture industries. It is evident that there is a substantial portion of the globally produced fly ash that is not recycled or re-used, and the need to develop new recycling methods or uses will intensify. Fly ash can for many reasons be seen as a resource, rather than a waste material. The recycling process of fly ash can conserve natural resources and energy. In the US the utilisation of fly ash in the cement industry accounts for a reduction of 10 million tonnes of greenhouse gas emissions annually.

The placing of CCP's, in particular ash, as a fill in open cast mines can have environmental and social benefits. The first being the regaining of the mined land for other productive uses, which can include grazing for animals or even the harvesting of food products when it can be performed in a safe manner. Secondly it can possibly eliminate the need for converting available land in close proximity to power stations to landfill sites for CCP dumps.

3. SOUTH AFRICAN PRACTISE AND COMPARATIVE PERSPECTIVE

3.1 INTRODUCTION

The South African coal fired power stations are situated in close proximity to the coal mines, where typical coal used has low calorific value and very high ash content (Kruger & Kreuger, 2005). Due to the high ash content of the coal used in the electricity generation process, high volumes of coal ash become available for storage. The convenience and availability of reasonably priced land near the stations allowed for the low-cost disposal of the fly ash, resulting in huge ash dumps with little value. The distances from economic hubs brought about by to the location of the South African power stations hinder the bulk usage of fly ash in industries due to high transport costs.

The disposal of CCP's causes significant environmental and economic difficulties for Eskom. The bulk of the coal ash produced are held in ash storage facilities, and to reduce the impact of the disposal of coal ash and in future the FGD gypsum it is imperative to seek alternative utilisation of these products. The WFGD system at Kusile power station will account for around 900 000 tonnes of FGD gypsum annually at full capacity.

South Africa is a country governed by *inter alia* legislation. The legislation that regulates the use and implementation of CCP's must be taken into account. These pieces of legislation can generally be seen as strict, as seen in the discussion below, and could be limiting the important uses for products such as fly ash. International utilisation and regulation of the CCP's in European Union and in particular Poland shows similarities, as well as differences when compared to South Africa.

3.2 NATURAL GYPSUM IN SOUTH AFRICA

Extensive surface to near surface gypsum deposits in South Africa are mostly concentrated in a belt over the Northern Cape Province and northern parts of Western Cape, also in the western Free State as indicated on Figure 3-1, as obtained from the Council for Geoscience. Natural gypsum deposits form in salt pans and in the upper portion of the weathering profile in the Ecca Group shales of the Karoo Supergroup. Gypsum deposits typically forms in areas where precipitation rates are low and evaporation rates are high. The richest gypsum fields in South Africa are located in the Bushmanland in the Northern Cape Province with deposits ranging from high grade 90% plus powdery gypsum to gypsum-clay mixtures with purities ranging between 65% and 85% (Van Straaten, 2002).

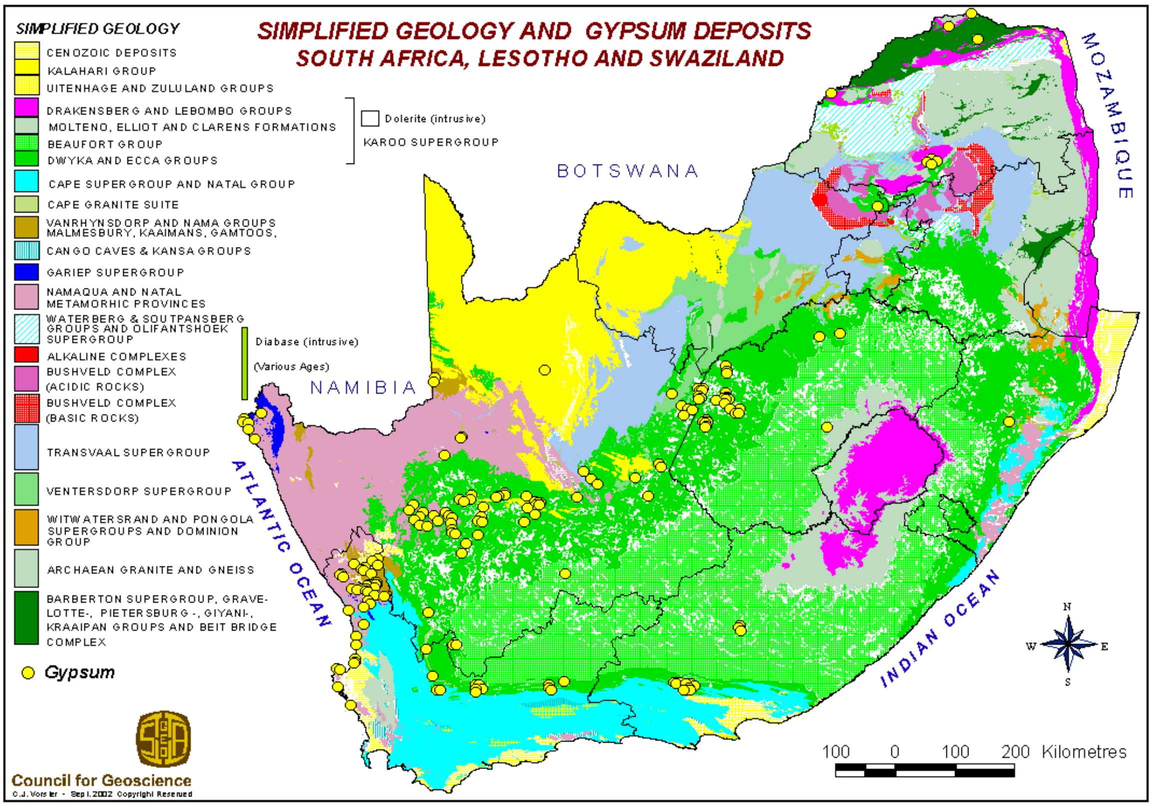


Figure 3-1 Gypsum deposits in South Africa (Council for Geoscience RSA, 2017).

The demand for gypsum in South Africa depends predominantly on the strength of the construction industry, which will have the biggest influence on the need for gypsum in the cement industry. The source of synthetic gypsum in South Africa is phosphor-gypsum which is a by-product of the phosphate fertiliser manufacturing process. Synthetic gypsum is in strong competition with natural gypsum deposits in the wallboard, agriculture and cement industry (Department of Minerals and Energy, 2003).

In 2016 an analysis was performed by Merchant Research and Consulting Ltd. on the import and export statistics of natural gypsum in South Africa. The 2015 statistics showed that South Africa exported 12 735 tonnes of anhydrite gypsum with a trade value of $705 664. South African gypsum is mostly exported to neighbouring or other African countries, Australia and Singapore. The highest percentage of anhydrite gypsum exported from South Africa is to Swaziland, Mozambique and Zambia as shown in Figure 3-2.

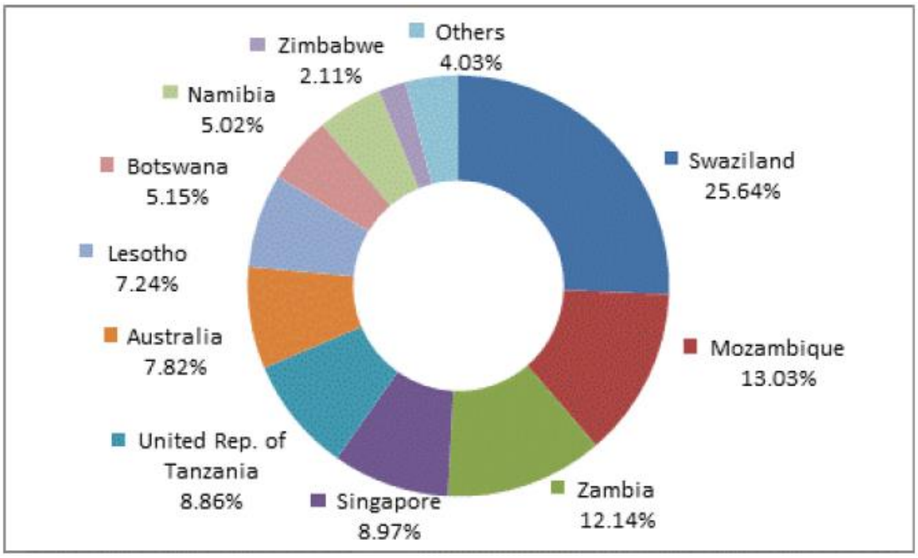


Figure 3-2 South African exports of anhydrite gypsum by country in 2015 Merchant Research and Consulting Ltd., 2016).

In 2015 South Africa imported 18 697 tonnes of anhydrite gypsum with a trade value of $916 157. The import statistics showed that 38.45% of anhydrite gypsum imported originated in Oman. Other large contributors of gypsum include the UK, Egypt and others as shown in Figure 3-3.

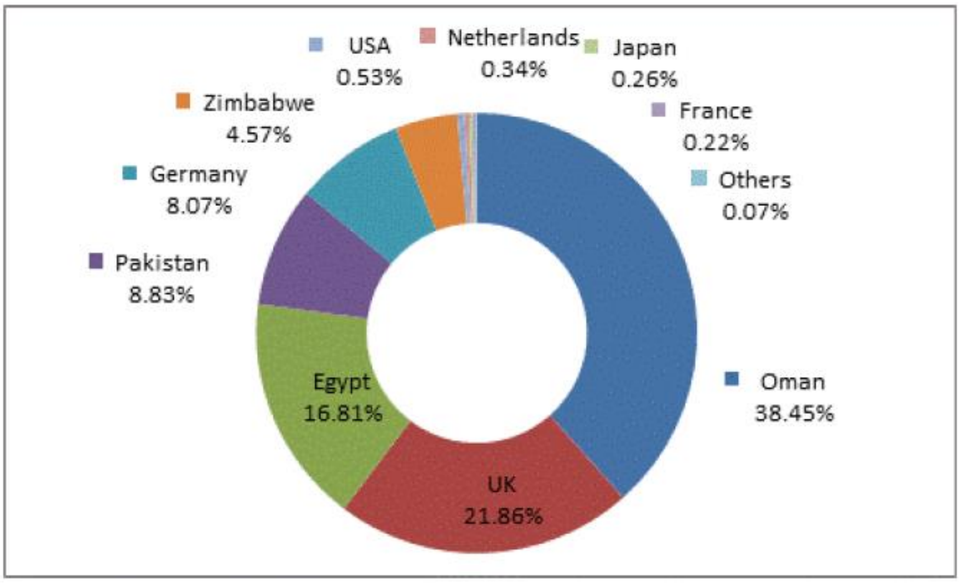


Figure 3-3 South African imports of anhydrite gypsum by country in 2015 (Merchant Research and Consulting Ltd., 2016).

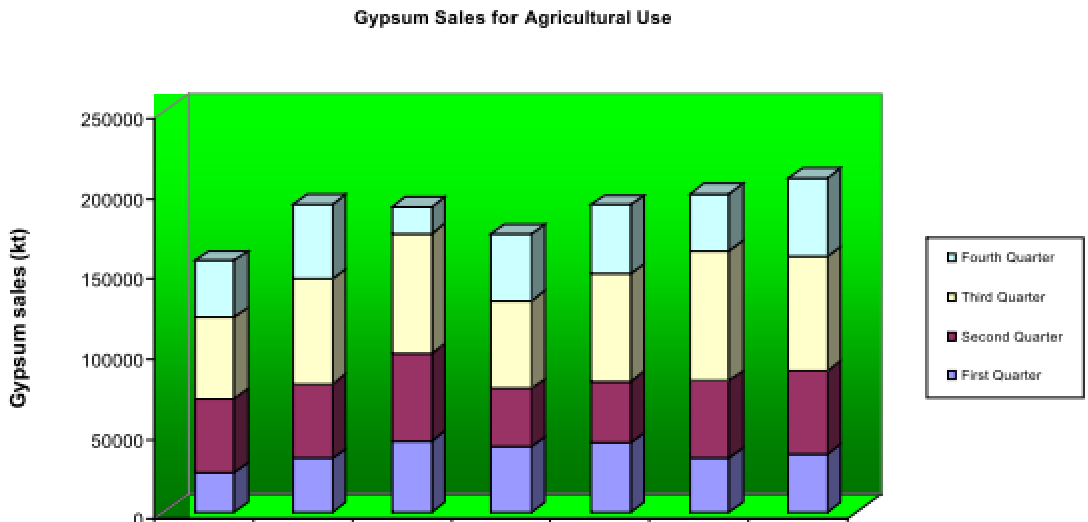
The trade prospects values in kilogrammes for anhydrite gypsum exports and imports for 2016 to 2020 are shown in Table 3-1.

Table 3-1 South African anhydrite gypsum trade prospects in kilogrammes (Merchant Research and Consulting Ltd., 2016).

	2016	2017	2018	2019	2020
Export	18 747 922	16 978 381	17 561 526	15 927 775	18 395 750
Import	16 844 144	17 928 897	21 056 138	18 520 422	17 952 418

3.2.1 Gypsum in the SA agriculture sector

The quarterly figures for the use of gypsum in the agricultural sector were released by the Fertiliser Association of South Africa (FERTASA) up until 2008. The Competition Tribunal confirmed a settlement agreement between SASOL and the Competition Commission in early 2009, after a small fertiliser company lodged a complaint at the Commission in 2003 against SASOL and three fertiliser companies. Nutri-flo lodged a complaint against SASOL in contravention to the Competition Act 89 of 1998 subsections 8(a), 8(c) and 9(1)(c) namely exclusionary pricing, excessive pricing and discriminatory pricing. SASOL pleaded guilty and paid a fine of over R250 million. After this case FERTASA decided not to make any statistics regarding the utilisation of any fertilisers available. The last available statistics for gypsum in South African agriculture use was obtained from a report prepared for Eskom by Over the Moon Environmental and Engineering Consultant services (2009). The statistics shown in Figure 3-4 was obtained from the FERTASA website in early 2009. The gypsum sales can be averaged at roughly 200 000 tonnes/annum, as the case was between 2003 and 2008.



	2002	2003	2004	2005	2006	2007	2008
Fourth Quarter	35325	46598	16913	41733	42871	35750	49130
Third Quarter	50542	65641	74612	54596	66970	80910	71046
Second Quarter	46119	46354	54644	36263	38371	48171	52143
First Quarter	24661	33258	44026	40644	43079	33637	35948

Figure 3-4 Representation of gypsum sales for agricultural use in South Africa (Over the Moon, 2009).

3.2.2 Gypsum in the SA cement industry

Gypsum is used as a retarder in the manufacturing of cement and it plays an important role in the hardening of cement. A small amount of gypsum, usually 5% - 6% of gypsum by cement mass, is added after the cooling of the clinker in the final grinding process. The purity of gypsum will depict the percentage added to the clinker because the final SO_3 content in the cement must be about 3% to ensure a stable product (Domone & Illston, 2001). South Africa produced approximately 12.75 Mega tonnes of cement in 2015 (Strategic Forum, 2016) and by using 5% of gypsum required as a retarder the gypsum usage in 2015 were 637500 tonnes. Cement manufacturing plants are mostly located in the Highveld region and Gauteng in South Africa, but there are also a few plants situated in other provinces. A few examples include: Pretoria Portland Cement (PPC) has two cement manufacturing sites in Gauteng and two located in the Western Cape; Sephaku cement has two cement manufacturing plants, one in the North West province and one in Mpumulanga; and Afrisam has one manufacturing plant in the Northern Cape, two in North West and three in Gauteng.

3.3 FGD GYPSUM IN SOUTH AFRICA

At the time of the initial Environmental Impact Assessment (EIA) for Kusile, Eskom had the objective to only dispose of ash in a designated ash disposal area. An investigation was launched at the time to determine the existing and potential prospects of using FGD gypsum as a commercial product. Gypsum was classified as a medium hazardous waste, based on an American sample, and Eskom had to apply for a Waste Management Licence to co-dispose the FGD gypsum with fly ash on site. A disposal site with a Class A liner will be utilised at Kusile power station for co-disposal of ash and gypsum for the first four years, where after it will be utilised for the storing of gypsum for the remaining of its ten-year life. The WFGD system at Kusile power station will account for around 900 000 tonnes of FGD gypsum annually at full capacity.

The application of FGD gypsum in industry will depend on the quality and characteristics of the end product. The three main industrial sectors utilising FGD gypsum comprise of the wallboard, cement and agricultural industries. Each of the three sectors have a different set of characteristics that has to be met with the quality or purity criteria ranging from a low 70% and up for agriculture (Pacific Fertilisers, 2015), 82% and above for cement manufacturing (Afrisam, 2016), to an almost pure 95% plus for the use in wallboard (Ramme & Tharaniyil, 2004). The quality of the FGD gypsum product is directly related to the quality of limestone used within the FGD process. The cost of the limestone used within the FGD process is based on the quality of the material and the logistics and transport costs. Raw material costs are sensitive and effectively a function of transport and handling costs.

Limestone deposits in South Africa are scattered over a few provinces as indicated on Figure 3-5 as obtained from the Council for Geoscience. D.G. Maxwell estimated in the early 1960's that the South African reserve of limestone deposits, capable of producing high quality lime, is in the range of 400 million tonnes (Douglas, 1969). The quantities of limestone available in reserves in South Africa are more than sufficient, but the location thereof can become an obstacle. Limestone sources containing more $CaCO_3$ are known as calcium limestone, which is typically used as a scrubbing agent in the FGD process, and is generally located further away. A report indicates that there are no limestone deposits within the limits of the Highveld coalfield area (van Heerden, 2004). Different limestone sources with varying quality are being tested by Eskom Research, Testing & Development (RT&D) to determine whether alternate sources will deliver reliable results within the FGD process. It is important to consider the quality of the FGD gypsum end product when compared to the quality of the raw limestone material used; this will finally determine the end use in industry. Limestone is a sedimentary rock primarily composing of calcium carbonate in the mineral form of calcite

(CaCO$_3$). Dolomite is a calcium magnesium carbonate with the chemical composition of CaMg(CO$_3$)$_2$. A siliceous calcite can also be known as a sand-calcite and it is a variety of the calcite mineral where crystals have grown with sand inclusions, the same applies to the siliceous dolomite. Ankerite is in its composition very similar to dolomite, the difference being the magnesium is replaced by varying amounts of iron (II) and manganese.

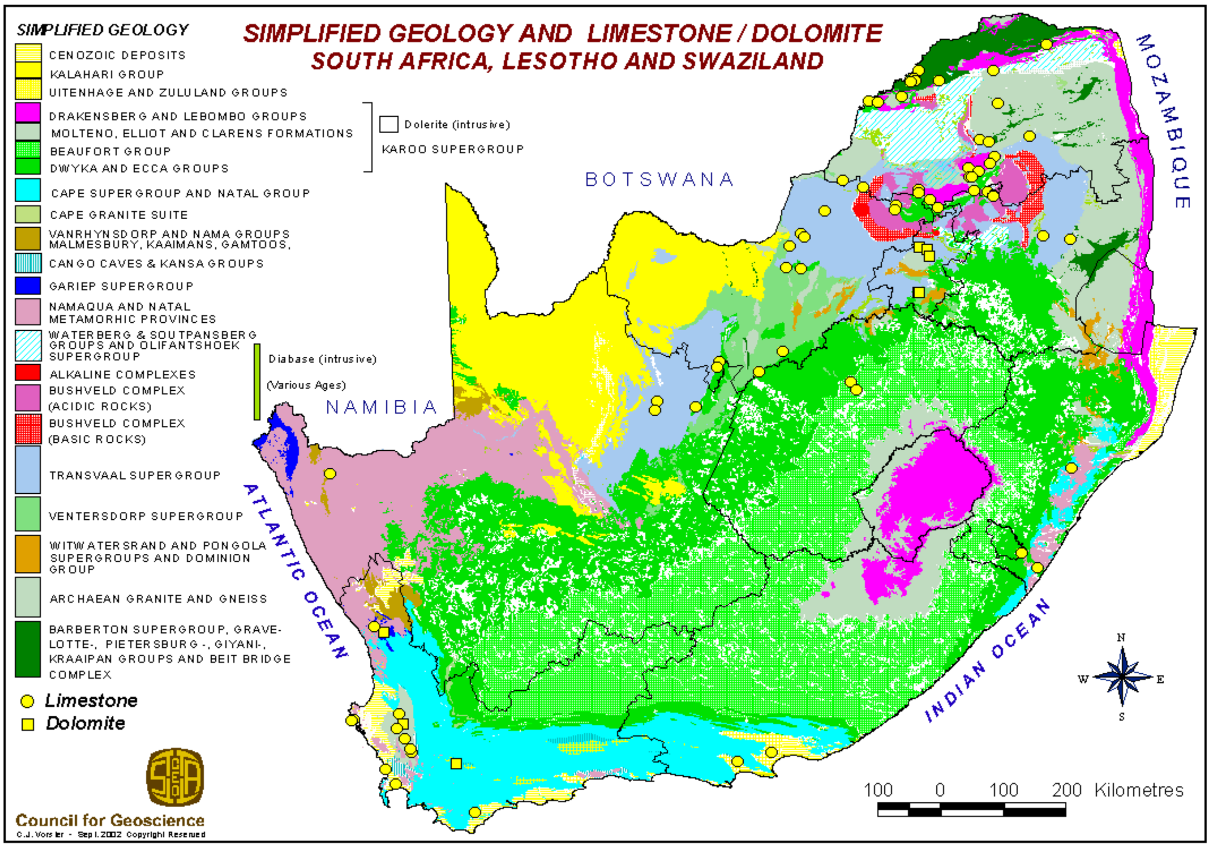


Figure 3-5 South African limestone deposits (Council for Geoscience RSA, 2017).

3.4 FLY ASH IN SOUTH AFRICA

In the late 1980's the South African cement industry decided to introduce fly ash blended cements in the market, which increased their capacity with minimum monetary investment. Blended cement products containing anything between 15% and 35% fly ash were marketed by the cement industry. The huge demand for fly ash in the construction industry required an assurance of consistent quality fly ash released into this sector. The Lesotho Highlands Project built the Katse Dam with around 40% fly ash blended cement to reduce cracking and limit heat build-up (Kruger & Kreuger, 2005). Equipment to beneficiate the fly ash by air classification was installed at Matla power station, and this air classified fly ash with a concentration of 90% 45µm particles and a carbon content of less than 1% became the SANS 1491-2 industry standard.

Classified fly ash is used as a cement extender due to a few very important properties which includes that it is spherical and pozzolanic, fly ash is non-expansive and low in alkalis, the carbon content is low and the classified ash also is of consistent quality. Fly ash as a cement extender increases the durability due to the removal of excess $Ca(OH)_2$ and also prevents an alkali-silica reaction. The utilisation of fly ash increased from around 20 000 tonnes/annum in the early 1980's (Kruger, 1997) to around 2.7 Mega tonnes/annum in 2015/2016.

The Eskom Integrated Report for 2016 showed that 114.8 Mt of coal was burned for electricity generation in the 2015/2016 financial year. A total of 32.6 Mt of ash was produced from the burning of coal during this same time frame. The utilisation of Eskom ash has increased from 7.35% in the previous financial year to 8.32% in the 2015/2016 financial year, as can be seen in Table 3-2. The increase in utilisation can largely be attributed to the new Eskom ash utilisation strategy which focuses on the development of the existing cement markets to its full potential. Other markets, including the brick making industry, are also explored to potentially increase the utilisation in bulk amounts.

Table 3-2 Eskom Annual Ash Figures (Eskom, 2016).

	2011/2012	**2012/2013**	**2013/2014**	**2014/2015**	**2015/2016**
Ash produced, Mt	36.21	35.3	34.97	34.41	32.6
Ash sold, Mt	2.3	2.4	2.4	2.53	2.71
Ash recycled, %	6.4	6.8	7	7.35	8.32

Eskom has adopted a Zero Liquid Effluent Discharge (ZLED) policy (Pather, 2000) in order to protect and reserve scarce water sources and to comply with environmental legislation. The ZLED policy requires all water to be treated on site. The ash dams and dumps play an important role within the treatment process where they act as a sink for effluents that has been reutilised to its maximum. If insufficient volumes of ash are available the dump becomes overloaded and the water leach pollutants into the ground water. The ZLED policy is not widely practiced in an international context due to the availability of water sources into which the effluent can be discharged in close proximity to power stations.

An engineering model was developed by Eskom Group Technology engineers on the amount of ash required per station to act as the effluent sink. This model was based on the figures for the 2011/2012 financial year when a total of 36.22 Mt of ash was collectively produced by all the power stations. The ash required for the effluent sink will constantly change as it is dependent on design based parameters, and for this reason the model is being examined by the Bulk Material Services department in Group Technology and will be revised and updated by late 2017.

Based on the 2011/2012 annual figures about 26.7Mt of the produced 36.2Mt of Eskom ash was used internally at all the power stations to treat effluent water. This relates to a figure of around 74% of the ash utilised within the stations. It is indicated that 19.6% ash was available for external utilisation or sales. If the assumption is made that a similar volume of ash was utilised internally for the effluent sink in comparison with the 2015/2016 ash figures, it will mean that 26.7Mt of the 32.6Mt produced was used. By keeping the 2.71Mt of ash recycled (sold) in mind, there was effectively only 3.19Mt of ash available for additional utilisation shown in Table 3-3.

Table 3-3 Eskom 2015/2016 annual ash figures (Eskom, 2016).

Total ash produced (Mt)	32.6
Ash used internally (Mt)	-26.7
Ash recycled (Mt)	-2.71
Ash available (Mt)	**3.19**

Figure 3-6 shows that the additional ash available for recycling amounts to 9.78% of the total ash produced. This narrates to a maximum possible utilisation rate of 18.1%.

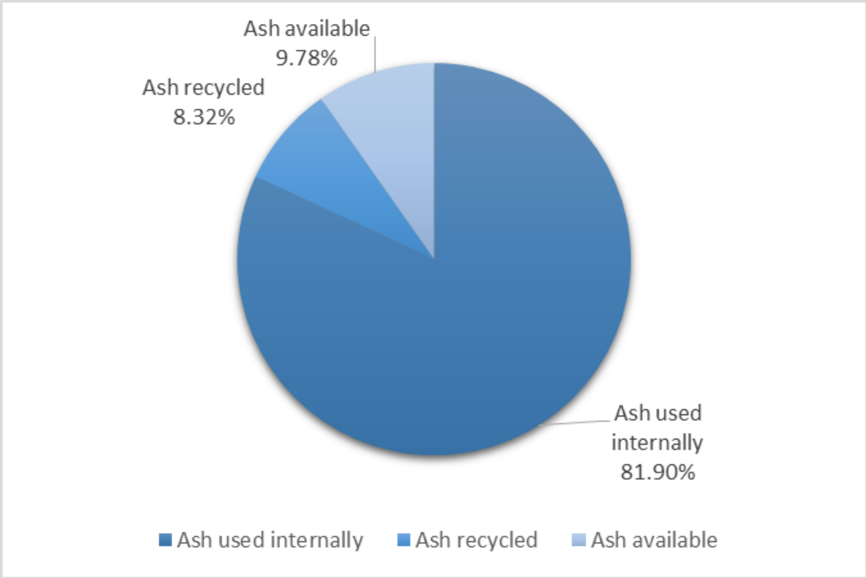
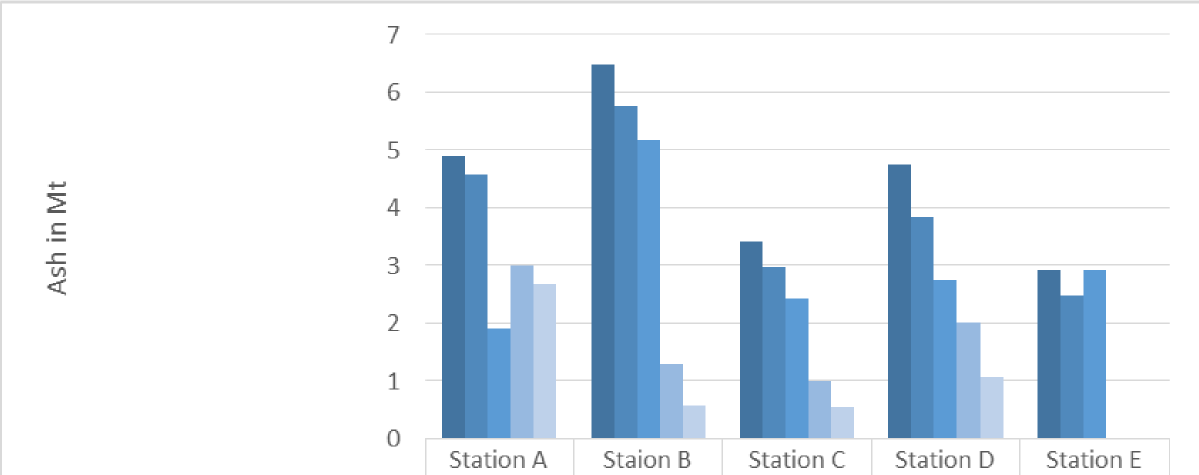


Figure 3-6 Eskom ash utilisation for 2015/2016 (Eskom, 2016).

A comparison is drawn between ash produced in the 2011/2012 and 2015/2016 financial years. If the ash utilised for the effluent sink is the same as the 2011/2012 figures, the updated ash availability at the dry ashing stations for 2015/2016 can be seen in Figure 3-7. Figures for the wet ashing stations can be seen in the Appendix.



	Station A	Staion B	Staion C	Station D	Station E
Ash Produced (Mt): 2011/2012	4.906	6.48	3.428	4.752	2.926
Ash produced (Mt): 2015/2016	4.583	5.763	2.975	3.83	2.481
Ash used for effluent sink (Mt)	1.906	5.18	2.428	2.752	2.926
Saleable (Mt): 2011/2012	3	1.3	1	2	0
Saleable (Mt): 2015/2016	2.677	0.583	0.547	1.078	0

Figure 3-7 Ash available at dry ashing stations.

The DEA introduced restrictions on disposal to landfill that has to be implemented by the end of 2021. "*Brine or waste with a high salt content (TDS > 5%) and a leachable concentration for TDS of more than 100 000 mg/l"* may not be disposed on landfill sites from end of 2021 (DEA, 2012). This new legislation will most probably only have an impact on the dry ashing stations where Reverse Osmosis (RO) rejects and demineralised train regeneration effluents are used for dust suppression. The new legislation will require the power stations to treat the brines to minimise the volumes to ensure only a small amount has to be disposed of as hazardous waste. Cooling water blow down used for the ashing process at the wet ashing stations ensures that the brines are significantly diluted and it will thus not trigger this new legislation. When this new legislation is adopted, it will require investment in water treatment technologies and will result in higher volumes of ash available for utilisation.

The three major off takers for Eskom ash are Ash Resources, Sephaku and Ulula. There are a few additional small role players, but the volumes that s removed by them is very small in relation to the three biggest ones. Ash Resources is responsible for almost two thirds of the off take and is a leading supplier of fly ash products in South Africa, with more than 30 years of experience in the industry. Ash Resources was founded in 1979 with key stakeholders at the time being Eskom and the cement industry. The Eskom share was sold to Poetona Group Holdings in 2009, and the other shares are owned by Lafarge South Africa. Ash Resources is responsible for a lot of the development of South African fly ash specifically for the construction industry. Lethabo, Matla, Kendal, Matimba and Majuba provides Ash Resources with ash. The highest volumes of Eskom ash recycled by means of sales are from Lethabo power station, with the main reason being its location in close proximity to the cement manufacturing industries. Ash Resources manages around 5 million tonnes of fly ash annually and after classification recycles around 1.8 million tonnes of Eskom ash.

Ash Resources produces some of the world's leading fly ash products. Production facilities are situated next to the mentioned power stations where fly ash is collected and conveyed to processing plants. The chemical and physical characteristics of the ash will determine in which product it will be utilised. Two products are manufactured from unclassified ash, where the one is used in general purpose cement products and the other used as an active replacement for fine aggregate in concrete. Ash Resources also manufacture products from world class quality classified fly ash. Some of the products are manufactured from Class S fly ash where 90% of the ash particles pass a 45µm sieve. A fourth improved air-cyclone classifier was installed at Matla power station resulting in the collection of a premium classified ash product. It is an improved and higher performance classified ash version based on the class S fly ashes, with an improved particle size distribution, an even finer grade, a higher concentration of glass-phase particles, consistent lower LOI value and even a better colour consistency. Ash Resources classified ash products has proven very successful in the Arabian Gulf as a cement extender to enhance the performance of concrete, especially in constructing buildings with architectural creativity. These products were used very successfully in the foundations and piles for the Burj Khalifa in Dubai, which at the time of completion was the world's tallest building. The research and development team at Ash Resources is responsible for manufacturing and testing new products, with products for use in mining applications awaiting change in legislation, as well as new products to be used as a filler in the rubber and polymer industries.

The bulk volume of the Eskom ash recycled or sold is utilised in the cement and construction industry. Fly ash can act as a cement extender and a percentage of the cement can be replaced with fly ash, depending on the end use of the cement product. The need for cement products in the construction industry is ultimately driven by the demand and growth of infrastructure. Figure 3-8 shows the domestic sales by month of cement in South Africa.

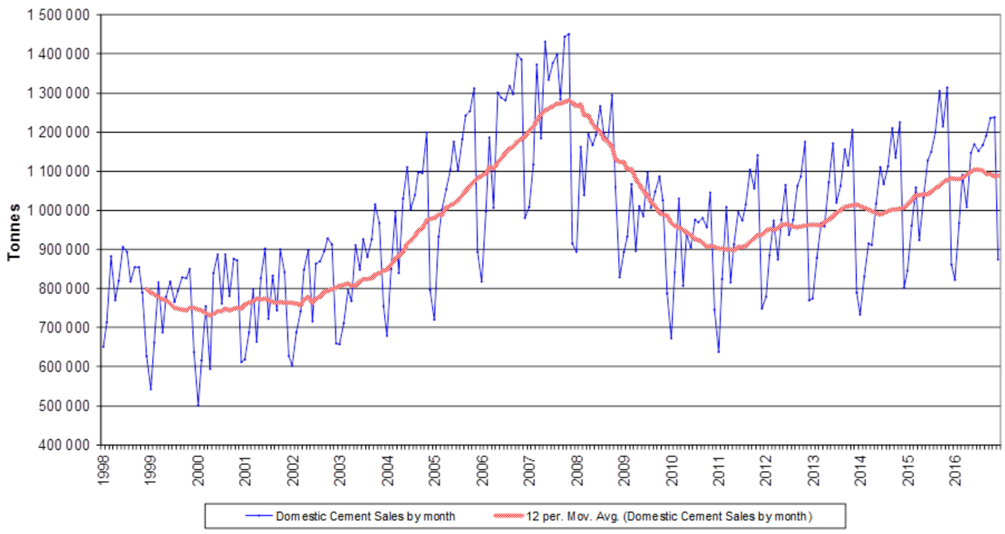


Figure 3-8 Domestic monthly cement sales in South Africa (Strategic Forum, 2016).

The upward trend until end of 2008 can be attributed to the construction of new developments for the 2010 Soccer World Cup and the construction of the Gautrain (Strategic Forum, 2016). It is also evident that there is a decrease in sales at the end of each year which coincides with the builders holiday break spanning from middle December to early January.

3.5 SOUTH AFRICAN LEGISLATION

The National Environmental Management: Waste Act (NEMWA) of 2008 communicates the law responsible for waste management in enabling the protection of the environment and human health. The Constitution of the Republic of South Africa (1996) stipulates that every citizen has the right to a safe environment and to keep it protected for future generations. The Waste Act also specifies that "*generation of waste is avoided, or where it cannot be avoided, that it is reduced, re-used, recycled or recovered and only as a last resort disposed of"* (NEMWA, 2008). This will promote sustainable living conditions.

The National Waste Management Strategy (NWMS) of November 2011 is a legislative requirement of the Waste Act. The purpose of the document is to assist in achieving the goals as set out by NEMWA. The objectives as set out in the Waste Act are positioned in accordance with the waste hierarchy of waste management throughout the lifecycle of a waste product. The main priority for waste management according to the NWMS is avoidance and reduction of waste, followed by re-use, recycling and recovery with treatment and disposal as the least favourable alternative. The goals as set out in the NWMS include the promotion of waste minimisation, re-use, recycling and recovery, creating of awareness on the impact of waste on human health and the environment and also to provide processes to remediate contaminated land. To achieve the waste management goals as set out in the NWMS the Waste Act provides different waste management measure documents. Waste Classification and Management, Licensing (which list activities that requires licenses) and Norms and Standards are just some of the documents in this Waste Management series.

The Department of Water Affairs and Forestry Republic of the Republic of South Africa released a waste management series of documents in 1998. The purpose of this document series is to upgrade the standard of waste management in South Africa and provide a regulation system for waste disposal. The first document is the Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste, which sets out a framework on hazardous waste identification and classification in terms of risks it poses to the environment. The requirements represent the lowest acceptable standard and requirements are set to ensure safe disposal. The document places waste into two classes, general or hazardous waste based on leach tests performed under acidic conditions.

General National Regulation (GNR) 634 – Waste Classification and Management Regulations released as part of NEMWA 2008 stipulates in section 4(2) that all waste generators must ensure that their waste is classified according to SANS 10234 within 180 days of generation. Classification of waste according to SANS 10234, based on the Global harmonised system for classification and labelling of chemicals. The classification criteria include:

- Physical hazards which is based on flammability, corrosiveness and others;
- Health hazards based on toxicity, carcinogenicity and others;
- Environmental hazard is based on toxicity to the aquatic ecosystem and distinguish between acute and chronic toxicity, bioaccumulation and biodegradation.

As per SANS 10234 a safety data sheet (SDS) must be produced for substances which meet the criteria for cut-off values as shown in Table 3-4. Constituents present in the waste material exceeding the values are used for classification in terms of health hazards. The environmental hazards are based on tests performed using Whole Effluent Toxicity Testing (WETT). WETT testing performed looks at the growth rate of *Selenastrum capricornutum* and the mortality rates of *Daphnia pulex* and *Poecilia reticulate*.

Table 3-4 Cut off limits/concentration limits for hazard classes (SANS 10234, 2008).

Hazard class	Cut-off value (concentration limit) %
Acute toxicity	> 1.0
Skin corrosion	> 1.0
Serious damage to eyes	> 1.0
Eye irritation	> 1.0
Respiratory sensitisation	> 1.0
Skin sensitisation	> 1.0
Mutagenicity: Category 1 Category 2	 > 0.1 > 1.0
Carcinogenicity	> 0.1
Reproductive toxicity	> 0.1
Target organ systemic toxicity	> 1.0
Hazardous to the aquatic environment	> 1.0

General National Regulation (GNR) 635 – *National Norms and Standards for the Assessment of Waste for Landfill Disposal* (2013), released as part of the NEMWA 2008, provides guidelines on barrier methods to eliminate the potential level of risk that the disposal of different waste types may have on the environment. The applicable terminology includes:

LC The leachable concentration of a particular element or chemical substance in a waste, measured in mg/l (ppm).

LCT The leachable concentration threshold limit for particular elements and chemical substances in a waste, expressed as mg/l (ppm).

TC The total concentration of a particular element or chemical substance in a waste, expressed as mg/kg (ppm).

TCT The total concentration threshold limit for particular elements or chemical substances in a waste, as expressed in mg/kg (ppm).

The TCT values with different thresholds for substances in wastes can be seen in

Table 3-5. A similar table with LCT values are available in GNR 635.

Table 3-5 TCT values for substances in wastes (GNR, 2013).

Substances in Wastes			
Metal Ions	**TCT0**	**TCT1**	**TCT2**
Arsenic, As	5.8	500	2000
B, Boron	150	15000	60000
Ba, Barium	62.5	6250	25000
Cd, Cadmium	7.5	260	1040
Co, Cobalt	50	5000	20000
Cr Total, Chromium Total	46000	800000	N/A
Cr(VI), Chromium (VI)	6.5	500	2000
Cu, Copper	16	19500	78000
Hg, Mercury	0.93	160	640
Mn, Manganese	1000	25000	100000
Mo, Molybdenum	40	1000	4000
Ni, Nickel	91	10600	42400
Pb, Lead	20	1900	7600
Sb, Antinomy	10	75	300
Se, Selenium	10	50	200
V, Vanadium	150	2680	10720
Zn, Zinc	240	160000	640000

A flow diagram of the process that ought to be followed to determine the waste type for the correct disposal is shown in Figure 3-9. The waste needs to be analysed to determine the leachable and total concentration of the elements as shown. The results of these concentrations are then compared to the LCT and TCT values to determine the correct waste type.

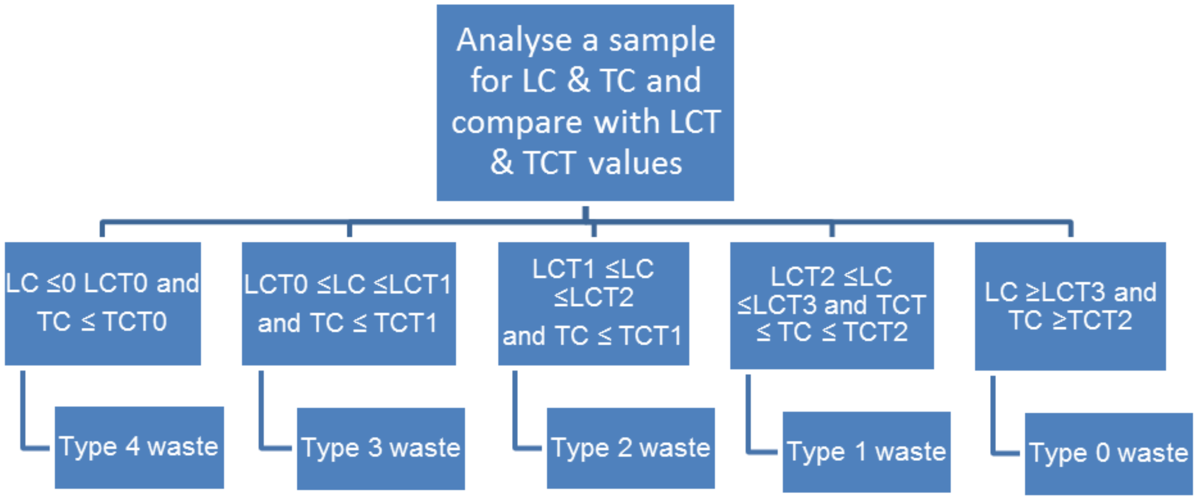


Figure 3-9 Flow diagram for waste type assessment per GNR 635 (2013).

The purpose of the classification of waste is to determine the class of landfill, which will result in utilising the correct barrier or liner for waste to be landfilled. The specific requirements for different classes of barriers can be found in Table 3-6 as per NEMWA Minimum Requirements for waste Disposal by Landfill No. R636 gazetted in August 2013. In applying for a license for a landfill site a full set of design calculations and drawing, signed off by a professional engineer, must be submitted.

Table 3-6 Waste disposal risk by type as per Norms and Standards (R636, 2013).

Waste Risk Level	Disposal Requirements
Type 0:	Disposal not allowed in landfill site.
Type 1:	Class A.
Type 2:	Class B.
Type 3:	Class C.
Type 4:	Class D.

The National Waste Information Regulations released as part of the Waste Act and Gazetted on 13 August 2012 classifies *Fly Ash and dust from miscellaneous sources* and *Bottom Ash* as both General Waste and Hazardous Waste. The fly ash classified as codes GW14 and HW14 and the bottom ash as codes GW15 and HW15. Persons or institutions performing activities that will result in waste classified in the Regulations must be registered on the South African Waste Information System (SAWIS). Quarterly reports on the waste source, quantity and other information as stated in Annexure 2 of the Regulations must be provided to the SAWIS. A Waste Management Licence (WML) is required for the handling, transportation, storage or disposal of registered waste. The NWMS stipulates that the private sector must take full responsibility for their wastes and products throughout the entire life cycle. Systems and waste management plans must be put in place to recycle wastes. Waste management technologies must be established to ensure that all waste products can be managed according to the hierarchy. The private sector must also comply with all conditions set out in waste management licenses.

The National Waste Management: Amendment Bill was approved by Parliament in February 2014 and it strives to address some of the challenges experienced with definitions in the document. The definitions for "waste", "re-use" and "recovery" is unclear and it becomes challenging to confirm the materials and activities that will trigger the need for a waste management licence. The proposed amendment to the definition of "waste" is as follows:

> *''(a) any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act;*
>
> *or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—*
>
> *(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered;*
>
> *(ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered;*
>
> *(iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or*
>
> *(iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste.''*

The Amendment Act introduces a Schedule 3 which provides a list of waste divided in hazardous and general categories, and will provide more certainty on what can be established as a waste. The Amendment Act shows that the definition for "recovery" is substituted by "*recovery means the controlled extraction of a material or retrieval of energy, any substance, or material or object from waste to produce a product"*. The amended definition for re-use is "*to utilise the whole, a portion of or a specific part of any substance, material or object from the waste stream for a similar or different purpose without changing the form or properties of such a substance, material or object*".

3.6 CCP'S IN POLAND

3.6.1 European Union and Polish Legislation

The EU Directive 2008/98/EC stipulates that the waste hierarchy in Figure 3-10 must be applied as the order to prevent waste and to bring about legislation and policies. EU member states must ensure that the options chosen for waste management have the best interest for human health and the environment. The lifecycle of the end product must be taken into account and if the impact can be decreased the hierarchy can be altered. Waste legislation developed per individual EU member country must be a transparent process where sustainability and the health of the environment and population must always be considered.

Figure 3-10 EU disposal hierarchy (EU Directive, 2008).

A summary of the most relevant articles in the EU Directive related to substances will follow. Article 5 in the Directive stipulates that any substance or material produced as a consequence of a production process where, the principle objective is not the production of that specific substance or material, can be considered as not a waste substance or material but as being a by-product when the following criteria are met:

- the utilisation of the substance or material after production is definite;
- no further processing (other than industry standards) is required before the substance or material can be utilised;
- the substance or material is produced as an essential part of the production process and
- utilisation of the substance or material after production is legal, and the utilisation of it will not have any negative impact on the environment or human health. Further use of the substance or material must satisfy all product requirements to ensure safe use.

Some substances or material that has been classified as waste can be declassified based on an “end-of-waste status” as prescribed in Article 6 of the EU Directive. The substance or material must meet the conditions of being used for specific purposes, a market must exist for it, all legislation and requirements must be met for the specific purpose and it must have no negative impact on the environment or human health.

EU member states may show evidence that specific substances or materials do not have to be classified as hazardous wastes because it has no hazardous properties. Hazardous properties include the substance being explosive, oxidising, flammable, irritant, acute toxicity, carcinogenic and others. The complete list with limiting values can be found in the Commission Regulation (EU) No 1357/2014 of 18 December 2014. This document replaces Annex III of the EU Directive 2008/98/EC. Considering the evidence provided, the hazardous waste list can be amended to exclude these substances. According to Article 7 in the Directive the declassification of hazardous waste cannot be accomplished by dilution or mixing of the waste in order to lower the hazardous concentrations of substances within the waste. Article 10 of the Directive stipulates that all measures must be taken into account to recover all possible wastes and also not to mix different waste materials at collection.

The re-use of waste materials within products must be promoted and encouraged by all EU member states as stipulated in Article 11. Collection facilities shall be erected where high quality recycling can have effect. The recycling sector must have high quality standards and technical, environmental and economic criteria for products have to be met. Specific re-use and recycling targets for waste has to be met by all EU members and it has to be reported every three years.

Based on the waste hierarchy as shown in Figure 4-4 disposal is the least favourable alternative for waste handling. Disposal of waste must take place in accordance with Article 13 of the Directive to ensure the protection of the environment and human health. The costs of waste management in the EU shall be carried by the waste producer or by the current (or even previous) waste holder; this is based on the polluter pays principle. The polluter pays principle indicates that the costs of disposing of waste must be carried by the holder of the waste, previous holders of the waste or the producers of the product manufactured from the waste (EU Directive, 2008).

The European Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste also states that under the polluter pays principle it is important to take into consideration any effect of landfill on the environment. All landfill sites must be monitored and managed according to strict technical standards and requirements. Treatment and recovery processes should be encouraged to reduce the waste destined for landfill. Continuous monitoring of the landfill sites must be performed to ensure that there is no adverse effect on the environment. Waste to landfill in the EU countries shall be classified as non-hazardous, hazardous and inert waste. The producer of waste that has no other option but landfill of the waste must apply for a permit to landfill. The costs associated with the landfill and continuous monitoring of the site must be calculated for a minimum period of at least 30 years and funds must be available for this total time period.

3.6.2 EDF Ekoserwis

EDF Ekoserwis in Poland has more than 25 years of experience in the management of CCP's. The main objective of the company is to ensure security of electricity supply at the EDF power stations they serve by safely removing these CCP's from site. All processes within the company are performed in a manner that is safe and non-hazardous to the environment. EDF Ekoserwis has permits, in accordance with the EU Directive and Polish Waste Act, to collect and process different CCP's, which includes fly ash, bottom ash and FGD gypsum. The CCP union in Poland (a similar entity like ECOBA in the EU) takes responsibility in overcoming barriers associated with the utilisation of CCP's in Poland.

EDF Ekoserwis sell nearly 500 000 tonnes of fly ash annually. This is collected from different power stations in Poland, mostly located in the lower Silesia region. The largest portion of fly ash, around 300 000 tonnes/annum, is sourced directly from Rybnik power station, which is located in the West of Poland in close proximity to the Czech border. Fly ash is used widely in the Polish industry and EDF Ekoserwis customers include the cement, concrete, prefabricated concrete, road construction, mining and agriculture industry. The company is constantly expanding its sales network by introducing new research projects and technologies.

The Polish Waste Management Act (2012) requires that the intended user obtain waste permits in order to handle waste materials. Pilot studies needed to be performed before the CCP's could be regarded as a safe-to-use material within different products. Evidence had to be provided after the conclusion of the studies to the EU Directive regarding the physical and chemical characteristics of the CCP's from independent laboratories. The duration of waiting time for acceptance of the substance as a safe-to-use material is approximately three months after a full application was processed.

Article 4 of the Polish Waste Management Act specifies that CCP's are classified as non-hazardous wastes. Permits for safe utilisation can be obtained from the Minister which states that CCP's are stable products and the company is under obligation to control the stability of the product within certain parameters. It is the waste management companies' responsibility to provide the authorities with waste management procedures; if it cannot be shown penalties will have to be paid. Quality testing is performed daily for most of the products manufactured from CCP's in Rybnik. The levels of elements within substances tests (toxicology testing) are performed twice annually where the physical, chemical and leaching capabilities of the substances are tested and confirmed. Radio-activity tests are also performed biannually.

The EU requirements for waste landfill are very strict and it is not possible to construct new landfill sites. The industries in the EU are thus forced to provide solutions and products for an increase in CCP utilisation. The CCP's collected from the different power stations are processed directly for usage in the civil and road construction industry, or within mining application products where it is used to fill mining voids.

The waste materials utilisation process requires a constant improvement of the technological sequence. To enhance the collection and distribution process, installations are used and continuously modernised to increase efficiency. The following installations can be found at the Rybnik power plant and EDF Ekoserwis distribution site:

a. Mieszalnia Spoin – A mixing line used to produce mining binders, cements and mortars in bags. CCP's are used in different ratios to produce specific products. The capacity of the installation ranges from 16 tonnes/hour to 20 tonnes/hour depending on the size of the bags in which the product is packed.
b. Suche Granulat – Granulates dry mixtures within eight containers. This installation is responsible for the production of road construction and mining binders in bulk

volumes. The production plant is equipped with two independent hubs and each has a capacity of 45 tonnes/hour.

c. Skanska – Produces slag (bottom ash) mixtures, road and railway aggregates, slag sand, ekostabilisations, mix stabilisations and mineral stabilisations (specifically for road construction). A combination of CCP's are used, consisting mostly of ashes and slags in a wet mixture. The output is around 120 to 150 tonnes/hour (6 truckloads).
d. Marini – used to produce ashes and slag products used in road construction with an output of approximately 120 tonnes/hour.
e. Nisbau – mobile installation that is easy to transport or move. It gives an output of 100 tonnes/hour (4 truckloads) when used for production of mix stabilisations or 60 tonnes/hour if used for producing road binders.

Substance Information Sheets (SIS) are available which give relevant information pertaining to the product identification and also a list of safe uses for the material. The SIS also states that the fly ash is classified as a non-hazardous material. The SIS mentions that though it is non-hazardous, the dusty physical form can cause irritation. This is addressed in the SIS, which provides first aid measures, exposure control, physical and chemical properties, stability and toxicology. The list of safe uses for fly ash as mentioned in the SIS as provided by EDF Ekoserwis includes:

- Manufacturing of coal combustion products;
- Mineral raw material in bound applications (cement, concrete, mortar etc.);
- Mineral raw material and construction material in bound and unbound applications (bricks and ceramics);
- Industrial use in bound applications;
- Professional use in stabilisation of waste, sewage sludge, wetlands and others.

3.6.2.1 EDF Ekoserwis: FGD gypsum in agriculture

FGD gypsum product for agricultural use is marketed as a fertilizer named "Agrosulca" by EDF Ekoserwis. Agrosulca is a calcium-sulphate fertilizer available in a fine crystalline powder form or as Agrosulca Plus in a granulated form. The FGD gypsum used in the agriculture sector cannot change the pH of the soil conditions, but it can be used as a stabiliser. FGD gypsum can also act as a supporter for nitrogen absorption within the soil, owing the soluble sulphur capabilities introduced. More traditional fertilisers like lime or NPK must first be used to alter the pH conditions of the soil. NPK fertilisers are primarily composed of three main ingredients, being Nitrogen (N), Phosporus (P) and Potassium (K). The purity, moisture and toxicity of the FGD gypsum are all very important factors for the use of it in the agriculture sector. One of the main agricultural off takers in Poland for FGD gypsum is the mushroom farms, where it is used in bedding products. The mushroom farms previously used milled limestone as their fertiliser and they made the modification of only using FGD gypsum. This decision was also justified economically with FGD gypsum being significantly lower in price. FGD gypsum can additionally be used as a filler for nitrogen fertilisers where it can then directly compete with milled limestone (EDF Ekoserwis, 2016).

3.6.2.2 EDF Ekoserwis: Fly ash in construction

Fly ash is a recognised addition to concrete in the construction industry in the EU, globally and in Poland. The addition of fly ash in the mixture enhances the workability, reduces the hydration heat, increases the strength over time and lowers the cost (due to the high cost of cement) as mentioned in chapter 1. In Poland, fly ash is used in prefabricated products like paving blocks, concrete fencing and retaining walls. Additionally, fly ash is also used as an additive in mortars, ready-mix flooring, adhesives and plasters. EDF Ekoserwis provides the concrete industry with the option of Class A or Class B fly ash, with the Class A ash being more expensive due the lower percentage of impurities. Class A ashes are used in the cement and concrete industries. In Poland only fly ash of Category N (as described in chapter 1) is available and research projects are currently in progress to attempt better separation of ash particles, in the hope of achieving Category S fly ash. Conditions for fly ash in concrete as stipulated in PN-EN 450-1 have to be met. PN-EN 450-1 has the following chemical requirements for the use of fly ash in concrete as shown in Requirements for use of ash in concrete in Poland -1:

Table 3-7 Requirements for use of ash in concrete in Poland (PN-EN-450-1, 2009).

Chemical properties	**Standard requirements**
Contents of Cl-	≤ 0,10 % of weight
SO3	≤ 3,0 % of weight
The content of free calcium and reactivated CaO	≤ 10,5% of weight
Contents of reactivated silica SiO_2	≥ 25 % of weight
Contents of the total of oxides (SiO_2, Al_2O_3, Fe_2O_3)	≥ 70 % of weight

All ashes sold by EDF Ekoserwis conform to the standard requirements set out in PN-EN 40. Declarations of performance according to the standard can be provided to all customers by EDF Ekoserwis.

3.6.2.3 EDF Ekoserwis: Fly ash in road construction

EDF Ekoserwis has developed stabilisation products that can be used in the subbase layers in road construction called “Ekostabilizations”. These products are manufactured from CCP’s, mainly fly ash and bottom ash. The potential of these CCP’s to bind and solidify is used. When water is added a reaction with the pozzolanic and calcium compounds within the CCP’s occurs which creates a strength within the material. The Ekostabilization products are used in road subbase layers as a pavement structural layer, as well as a frost protection layer. The product can be used in a variety of road construction sectors, whether it is in a subbase of an airport road or parking area. It can also be used to broaden and reinforce existing pavement structures. Ekostabilization products providing final strengths varying between 1.5MPa and 8MPa are available from EDF Ekoserwis. The higher the final strength value, the higher the percentage of additional materials (in this case cement) in the mix design. The alkaline properties of the CCP’s within the Ekostabilization products are very similar to traditional cement and lime binders, therefore the product can be used as a material with no harm to the environment.

Mix and mineral stabilisation products are natural materials like sand and gravel mixed with fly ash and bottom ash. This product is used in a similar way to the Ekostabilization as a structural layer in the subbase layer of road construction. It can also be used for soil stabilisation and frost protection. The 28-day strength for this product varies between 0.5MPa and 9MPa. Bottom ash (boiler slag) can be used as a replacement material to natural sand in backfilling, bedding layers in small concrete elements and for the maintenance of roads in winter by acting as a coarsening aggregate. As mentioned it is not possible to construct new landfill sites, but it is also becoming a requirement to use weathered ash from existing landfill sites. Material from existing landfill sites are successfully utilised by EDF Ekoserwis in road construction stabilisation products. A mix ratio of round 2:1 is used by mixing two parts of the new fly and bottom ashes with one part of the “old” landfill material.

Activities performed by EDF Ekoserwis are enhancing environmental benefits by not storing ashes on landfill sites. UTEX that forms part of the current EDF Ekoserwis, performed research in the late 1980’s on the applicability of using ashes in mining applications. Their research proved that the utilisation of ash in excavated coal mines brings benefits to the mining industry and the environment. Research and pilot studies performed were done in accordance with legal regulations regarding industrial utilisation of energetic wastes. The research included physical and chemical studies, properties of ash and water mixtures, toxicology evaluations and the feasibility of technical solutions. Ashes are used to fill mining voids and seal excavations. Mixtures of ash and excavated mine aggregates are used in land reclamation of previous industrialised areas. These mixtures are also utilized in excavated mining areas as a fire prevention material sprayed onto cavity walls.

3.6.2.4 EDF Ekoserwis: Fly ash in mining applications

EDF Ekoserwis is a global leader on the utilisation of fly ash in mining applications, especially in the utilisation of ashes as fire prevention materials. The Universities in Poland are actively involved in research to enhance the mix ratios of materials within the mining binder products. EDF Ekoserwis produces different types of concrete-ash mineral mining binders that have been used in underground mining constructions since 1993, which includes:

- Early supporting structure with an ultimate strength of more than 40MPa. The product is water resistant and is used for supporting strips, emergency stoppings and shotcrete.
- A late supporting type with a final strength of 15MPa to 20MPa. This product is also water resistant and used in a similar way than the early support type but has a lower strength.
- A filling binder used in a similar manner but with an ultimate strength of 5MPa.
- A mineral granular mining binder with escalated compression strength within the first three days of hardening and a final strength of 30MPa.

The mineral binders can be used within underground construction by pneumatic or hydromechanics means of transportation. Mining binders are not usually used in wet areas underground. The mixtures typically consist of ashes, cement and brine water. Ashes are mostly transported to the mining site in a dry powdery state by means of rail transport or on a smaller scale by trucks. Category B ashes, as mentioned above are mostly used in mine backfilling applications. The retention time for the storage of ashes in Rybnik is four days. The ashes that are not sold and used in other products will be used in mining. In the winter months when construction is not taking place due to the low temperatures all available ashes are used in mine backfilling.

3.6.2.5 EDF Ekoserwis: Fly ash in cellular concrete

EDF Ekoserwis supplies Class A fly ash to PREFABET Bielsko Biala, a company responsible for the manufacturing of high quality cellular concrete. Cellular concrete is aerated autoclaved concrete with a very high thermal capability. The material used by PREFABET in these concrete blocks includes fine limestone, fly ash, natural gypsum and water. The hydrated form of FGD gypsum can be detrimental in the chemical hydration process and it cannot be used in these blocks. It is noticeable that no cement is used within the product.

The cellular concrete blocks undergo a natural chemical hydration process where the temperature of the mixture rises to 86.4ºC within 4 hours. After the initial heating process, it can be cut in the desired size, where after it is placed in an autoclave at a pressure of 10 bar and a temperature of 200ºC for 12 hours. The advantage of this construction material includes the following:

- the high thermal capability enables the use of it in areas with high temperature variations;
- the aeration process increases the fire resistance capabilities of the material;
- light weight material enables ease of transportation;
- the bigger size of the block compared to traditional clay bricks can speed up the construction process. Though no cement is present in the mixture, the strength obtained ensure usage in building up to three stories and
- greener building material due to the exclusion of cement in the manufacturing process.

3.7 COMPARATIVE STUDY

3.7.1 SA vs. EU legislation comparison

The EU Directive stipulates the waste hierarchy from the bottom up as prevention, re-use, recycling, recovery and as a last resort disposal. This is similar to the conditions stipulated in the South African Waste Act where the same hierarchy follows with disposal as the least favourite alternative.

According to Article 5 and 6 in the EU Directive all CCP's can be classified as a by-product and not a waste because evidence was provided that the materials can safely be utilised in specific end products. In South Africa CCP's are classified as hazardous waste materials per the National Waste Information Regulations which requires WML. The new definition of "waste" in the SA Waste Act Amendment Bill enables industries to create new opportunities where certain wastes can now become a product, when it ceases to be a waste. This is a similar approach implemented in Europe by industry stakeholders.

A motivation may be submitted to the Minister of Environmental Affairs to list a specific activity as an activity that does not require a WML under Regulation 9 of GNR 634. The motivation must demonstrate that the waste management activity, which includes transport, handling and storage, can be performed consistently in a controlled manner to ensure no impact or risk on human health and the environment. An extensive list of information (as shown in GNR 634) is required to complete the requirement of the motivation. Some of the information required includes:

- the benefits of the proposed activity, in particular it must be shown how the activity will minimise landfill volumes;
- all physical and chemical characteristics of the waste must be presented and
- information on successful implementation of the proposed activity or similar activities either locally or internationally.

South African products generated from the coal combustion process cannot be delisted as a waste, but if an application under Regulation 9 is approved no WML will be required for specific activities. The high cost of applying for a South African WML and coinciding strict norms and standards hinders smaller companies to utilise ashes at present. By applying for a WML all waste monitoring, handling practises and procedures must be included. Results from laboratory projects and/or pilot studies have to be included to show the impact that the project may possible have on the environment. The Regulation 9 process in South Africa can be similar to the process described in Article 7 and 10 of the EU Directive.

Re-use and recycling of materials are largely promoted in the EU, as stipulated in Article 11 of the Directive. Very strict re-use and recycling targets has to be met every three years by waste producers. The costs associated with landfill disposal of EU wastes are very high and continuous monitoring must be performed for 30 years after disposal.

The utilisation of South African CCP's at low percentages and the vast amounts produced leads to the alternative of landfill disposal. Strict classification processes have to be followed, as set out in GNR 635 to determine the type of waste for landfill. The type of waste will determine the class of liner required for landfill.

3.7.2 Poland vs. SA ash samples

The elemental analysis of three ash samples used in the Poland mining industry has been provided by EDF Ekoserwis. Table 3-8 shows the XRF values of the three samples unitised without LOI. All three samples can be identified as Class F fly ash with the sum of the SiO_2, Al_2O_3 and Fe_2O_3 being more than 70% of the total weight, as in Table 1-2.

Table 3-8 Polish ash elemental analysis unitised on an oxide free basis in wt. % .(EDF Ekoserwis, OPINIA 72.19.2, 2016).

	Sample 1	Sample 2	Sample 3
SiO_2	53.38	52.27	54.01
Al_2O_3	28.60	27.18	27.64
Fe_2O_3	5.98	6.61	6.58
TiO_2	1.19	1.15	1.10
P_2O_5	0.62	0.96	0.42
CaO	3.20	3.71	3.08
MgO	2.02	2.66	2.29
Na_2O	0.97	1.29	1.04
K_2O	3.50	3.69	3.40
SO_3	0.54	0.49	0.43
	100.00	100.00	100.00

Results for XRD analysis performed on 13 of Eskom's power stations (excluding Kusile and Medupi power stations) are available in Table 3-9. The results also show typical Class F fly ashes when compared to Table 1-2. The Polish and Eskom ashes are very similar with the biggest difference probably the CaO content. The polish ashes have on average around 3.33% CaO content, where the South African ashes has an average CaO content of closer to 5%. The higher the CaO content within the material the more natural cementing capability it has. Class C fly ashes typically have a higher lime percentage and Portland Cement has a percentage ranging between 61% and 67% (Lutze & vom Berg, 2010).

Table 3-9 Eskom ash elemental analysis on an oxide free basis (Reynolds-Clausen, 2016).

Stations	A	B	C	D	E	F	G	H	I	J	K	L	M
SiO_2	53.72	56.63	53.43	57.47	53.71	54.32	53.16	56.59	55.37	53.75	53.50	54.01	53.44
Al_2O_3	31.57	30.50	31.19	28.28	30.14	30.66	30.68	28.96	29.24	34.42	31.39	27.16	29.72
Fe_2O_3	3.24	3.58	4.33	6.51	5.97	4.73	5.04	4.74	5.12	5.07	3.96	4.05	3.36
TiO_2	1.72	1.59	1.91	1.53	1.72	1.75	1.79	1.65	1.71	1.96	1.88	1.62	1.73
P_2O_5	0.74	0.45	0.67	0.51	0.56	0.51	1.12	0.53	0.61	0.55	0.90	0.69	0.96
CaO	5.67	4.87	5.63	3.15	4.65	5.04	5.04	4.64	4.72	2.38	5.21	8.31	6.51
MgO	1.92	1.19	1.51	1.02	1.21	1.75	1.47	1.44	1.41	0.62	1.77	1.72	2.14
Na_2O	0.40	0.30	0.10	0.31	0.91	0.21	0.21	0.21	0.40	0.10	0.21	0.30	0.71
K_2O	0.81	0.70	0.80	0.81	0.71	0.62	0.74	0.72	1.00	0.93	0.83	0.91	0.81
SO_3	0.20	0.20	0.40	0.41	0.40	0.41	0.74	0.52	0.40	0.21	0.31	1.22	0.61
MnO	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

XRF analysis on the Polish ash samples has also identified the heavy metals within the material as shown in Table 3-10. Comparing these values to the TCT limit values in Table 3-5, as set out in GNR 635, the Arsenic, Barium, Copper, Manganese, Antinomy and Zinc TCT0 levels are triggered, thus classifying the Polish fly ash samples as a Type 2 or 3 waste. Leachate tests and LCT values in conjunction with the TCT values will determine whether the substance can be classified as a Type 2 or 3 waste. The values under scrutiny are highlighted in grey in Table 3-10.

Table 3-10 Polish ash heavy metals as per ICP (EDF Ekoserwis, OPINIA 72.19.2, 2016).

	Sample 1	Sample 2	Sample 3
Arsenic, As	30	32.3	17
Barium, Ba	1123	1436	1166
Cadmium, Cd	<2	3.52	<2
Co, Cobalt	15	49.7	12
Cr(VI), Chromium (VI)	130	153	115
Cu, Copper	104	116	85
Mn, Manganese	497	606	534
Mo, Molybdenum	3	7.32	4
Ni, Nickel	97	99.9	86
Pb, Lead	126	230	91
Sb, Antinomy	3	20.3	4
V, Vanadium	221	266	198
Zn, Zinc	310	309	204

The heavy metal concentrations of ten of the thirteen ash samples obtained from Eskom power stations are available as per XRF analysis in Table 3-11. By utilising the flow diagram in Figure 3-9 and comparing the measured concentrations with the TCT values in Table 3-5, it is noted that Arsenic, Barium and in some samples Nickel triggers the TCT0 levels. By the assessment, the fly ash can be classified as either Type 2 or Type 3 waste, depending on the LC values obtained from leachate testing. It is evident that the Polish fly ash and the South African fly ash samples are within similar elemental and heavy metal ranges.

Table 3-11 Eskom ash heavy metal analysis as per XRF (Reynolds-Clausen, 2016).

	A	B	C	D	E	F	G	H	I,J,K	L	M
Arsenic, As	14.0	14.4	11.4	19.7	23.3	38.1	20.3	27.2	n/a	24.8	23.0
Ba, Barium	959.7	895.6	832.9	860.7	813.3	977.5	983.9	926.1	n/a	1589.3	1675.5
Cr(VI), Chromium (VI)	280.9	337.6	394.6	255.2	405.3	421.4	518.3	313.1	n/a	280.1	231.6
Co, Cobalt	7.3	7.7	14.3	17.3	30.0	31.0	17.4	15.4	n/a	5.8	6.7
Cu, Copper	25.5	29.7	28.5	27.9	25.1	28.7	29.0	25.6	n/a	36.6	31.7
Mn, Manganese	280.4	331.6	445.7	600.3	348.4	565.1	452.6	193.6	n/a	382.1	327.0
Ni, Nickel	79.4	78.4	138.3	81.9	145.0	133.7	186.0	86.3	n/a	91.6	68.1
Se, Selenium	3.4	4.1	3.3	4.0	5.3	4.7	4.0	6.7	n/a	6.4	3.0
V, Vanadium	78.6	99.2	69.8	116.6	91.4	115.6	82.7	77.1	n/a	93.6	76.8
Zn, Zinc	28.4	40.6	38.7	100.3	43.5	77.0	49.9	64.4	n/a	17.6	24.5

3.7.2.1 Ash Resources vs. EDF Ekoserwis

EDF Ekoserwis and Ash Resources are similar companies and both handles coal combustion waste from power stations. Ash Resources sells almost four times the volume that EDF Ekoserwis dispose of annually. Ash Resources has a world leading product portfolio with global projects utilising the products. South African classified ashes of Class S are not available in Poland, and that is a big advantage for the South African industry. More markets can be unlocked in future in South Africa for the better classified ashes.

EDF Ekoserwis has a bigger variety of products available for different sectors. The mining and road binder application products have been well researched and it can easily be applied in construction activities. Ash Resources has started with the development of classified ash based products for the road and mining industry, however, the legislation process in South Africa has hindered the development of products for other sectors.

Due to strict legislative constraints ashes are not utilised in the South African mining industry. Bulk volumes of ash can be utilised to fill voids and prevent AMD water formation. Large sums of capital and operational expenses will have to be incurred to ensure technologies of transportation and placement of ashes into the mining voids can be put in place. When the application under Regulation 9 is approved for the utilisation of CCP's in mine backfilling, a pilot study will have to be launched to determine the effect that CCP's in the voids will have in a South African Environment. Professor Leslie Petrik from the University of Western Cape (UWC) is involved with ongoing research regarding the utilisation of South African fly ashes to treat AMD. Along with her team she has performed numerous studies at different scales to investigate the potential of using ash to neutralise the very acidic AMD water. The results obtained by the smaller scale studies showed that the treatment method can indeed be very effective. The laboratory scale tests needed further optimisation before it can be implemented in full-scale. The necessary licenses are required for pilot scale implementation to obtain relevant result. The biggest concern in South Africa between Eskom and the mines is related to the liability in case of environmental harm.

EDF Ekoserwis utilises mostly bottom ashes in subbase layers of road construction. Ash waste form old landfill areas are mixed with fresh ashes and used in the bottom road construction layers. In South Africa the use of fly ash as a binder in road construction will have to be researched and check with the Heavy Vehicle Simulator Testing (HVST) equipment at the CSIR to check compliance with road standards.

Utilising CCP's, in particular FGD gypsum, in agriculture is an approved activity in Poland (EDF Ekoserwis, 2016). The advantageous of using FGD gypsum as a soil conditioner and fertiliser has been proven extensively. In order for South Africa to utilise ashes and gypsum in agriculture as a soil amendment or conditioning material, research will have to be conducted to verify that it does indeed have a positive impact on South African soils. The research process in agriculture takes a minimum of three years to determine the effect on the soil and corresponding groundwater. Leachate tests are performed according to the Australian LEAF standards and this is a very time consuming process.

3.8 CHANGE IN SA LEGISLATION

Eskom submitted an application under Regulation 9 in late 2016 to the DEA for the activities of brick making, road construction, mine backfilling and agriculture to be approved as activities that do not require WML's in utilising fly ash. An application was also filed under

Section 74 for the exemption of a WML for the activity of brickmaking. Interested parties could apply and had to make sure that they comply with a strict set of Norms and Standards. A summary of the Norms and Standards associated with a Section 74 application for the use of ashes in brick making follows (Exemption Reference: 12/9/11/L66006/3/LE):

1. Conditions for handling the ash:
   The ash may only be used for brick making and it may not be sold to third parties. Records must be kept on site of deliveries, monthly reports and Safety Data Sheets (SDS). The ash must be covered to reduce dust emissions.
2. Duty of care:
   Safety measures are provided against the pollution of water resources, spills and clean up and also leachate and dust management.
3. Delivery of ash to off takers:
   Requirements are provided regarding the safe transportation of materials.
4. Storage of ash:
   Ash may only be stored in demarcated bunded areas which are lined to reduce the risk of seepage and contamination.
5. Training:
   All employees must receive environmental awareness training and wear the appropriate personal protective equipment (PPE).
6. Audits:
   External audits will take place on an annual basis. The reports must show whether the conditions of the standards are adhered to as well as monitoring results. DEA can do audits at any facility without prior notice.
7. Reporting:
   All ash facilities must be able to provide verification documents at request regarding storage, handling, transportation, health and safety and disposal.

If the application is successful the exemption is valid for a two year period and it can thus be seen as a very good interim solution whilst waiting for approval under Regulation 9.

DEA released a Government Notice in the Government Gazette of 2 June 2017 proposing regulations to exclude certain waste streams from the definition of waste under NEMWA (2008). The Waste Exclusion Regulations (2016) will come into effect on publication date. Section 8(1) states that "*the waste streams listed within these Regulations is restricted to the identified prescribed uses in these Regulations*". The Regulations state that when a waste stream has been excluded from the waste definition it may be recovered without a WML, conforming to a set of norms and standards for handling. It is proposed in the Notice that ash from combustion plants may be exempted from the waste definition for the following uses:

- Brick making;
- Block making;
- Cement production;
- Landfill capping;
- Backfill in old mine workings;
- Inorganic fertiliser;
- Soil ameliorant;
- Asphalt and bituminous mixtures;
- Road construction and
- Bulking agent for compost.

The Norms and Standards document that will have to be adhered to for each activity is still in development and not yet finalised.

3.9 SUMMARY

South African practices with regards to fly ash and gypsum is limited to the construction industry. The South African legislation regulating the utilisation and categorization of the CCP's are the prescribed in the National Waste Act and set of addendums documents. Poland falls within the European Union. A comprehensive study regarding Poland's successful utilisation of CCP's within different application areas was done. This study indicated that CCP's are effectively utilised in the construction, road building, agriculture and mining environments. The European Union stipulates in its policies that all CCP's are classified as by products and not waste products. EDF Ekoserwis is a company in Poland that specializes in the effective management and product creation of CCP's.

A comparison was drawn between the legislation regulating CCP in both South Africa and the EU. This indicated that South African waste classification practises are much stricter in the current time and perhaps a few years behind in environmental legislation terms. The classification of CCP's in South Africa hinders the development of products and the utilisation thereof. The classification of EU CCP's as by products enables the utilisation of it in a bigger spectrum of applications.

General National Regulation (GNR) 634 – Waste Classification and Management Regulations released as part of NEMWA 2008 stipulates in section 4(2) that all waste generators must ensure that their waste is classified according to SANS 10234 within 180 days of generation. The under-utilisation of vast amounts of CCP's produced in South Africa creates the alternative of landfill disposal. A motivation may be submitted to the Minister of

Environmental Affairs to list a specific activity as an activity that does not require a Waste Management Licence (WML) under Regulation 9 of GNR 634. The motivation must demonstrate that the waste management activity, which includes transport, handling and storage, can be performed consistently in a controlled manner to ensure no impact or risk on human health and the environment. South African products generated from the coal combustion process cannot be delisted as a waste, but if an application under Regulation 9 is approved no WML will be required for specific activities. The high cost of applying for a South African WML and coinciding strict norms and standards hinders smaller companies to utilise ashes at present and it can be similarly problematic for the FGD gypsum. By applying for a WML all waste monitoring, handling practises and procedures must be included. Results from laboratory projects and/or pilot studies have to be included to demonstrate its impact on the environment.

In late 2016, Eskom submitted an application under Regulation 9 to the DEA for the activities of brick making, road construction, mine backfilling and agriculture to be approved as activities that do not require WML's in utilising specifically fly ash. A similar application will follow at a later stage when stable samples of FGD gypsum are produced at Kusile power station and the characteristics of the end product is more certain.

Samples of ash from both Poland and South Africa was studied and compared to the South African legislation parameters. This comparison gave way to knowledge portraying that the fly ash from Poland and South Africa show stark similarities in terms of elemental composition and heavy metals. The ash samples from both countries can be classified as Class F ashes and classification of type for landfill disposal is Type 2 or 3 waste, depending on the leaching capabilities.

The main difference between the South African and Polish scenario is the volumes of ash created annually. South African ash has a very high ash content and the vast amounts of ash created is much more than in Poland. The comparison study has shown that there are a lot of similarities between the ash samples and if legislation can be changed in South Africa, fly ash can be applied in similar products as in Poland.

4. METHODOLOGY: EXPERIMENTAL

4.1 INTRODUCTION

A limestone sample was obtained from EDF Polska in Poland along with a corresponding FGD gypsum sample. The Polish limestone and gypsum samples were used as a reference to predict the quality of gypsum synthetically obtained from three different South African limestone sources. The quality of the gypsum samples was determined with x-ray fluorescence (XRF) analysis, Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) and thermogravimetric analysis (TGA). The ultimate goal of the experimental study was to determine the applicability in a South African market.

4.2 MATERIALS USED

4.2.1 Limestone sampling and preparation

The Polish limestone sample was sourced from a natural mineral depository, the Ostrowka Quarry, in the Lesser Poland region close to Lublin. The specification from the supplier stated that the limestone is of a very high purity and consistently delivers FGD gypsum with a quality of over 95% to ensure that it meets the EUROGYPSUM specification for a product. The limestone sample arrived in South Africa in a 20kg plastic bag. The particle size of the sample was 45μm, corresponding to WFGD plant conditions in Poland. The sample was split with a rotary splitter in order to create a homogenous sample of approximately 250g.

The three South African limestone samples investigated have the following characteristics in terms of quality and source:

- Limestone A was sourced from the North-Eastern parts of the Northern Cape Province and has a $CaCO_3$ purity of 95% based on supplier specification. The limestone sample is dark grey in colour.
- Limestone C was obtained from the central region of the North West Province with a $CaCO_3$ purity of 90.8% as per the supplier specification. The limestone C sample had a sandy colour and
- Limestone K originates from the Northern parts of the North West Province in very close proximity to the Limpopo provincial border, and has a $CaCO_3$ purity of around 70% as per supplier specification, also with a sandy colour.

The sample annotations A, C and K correspond to a study performed by Pieter Swart (Eskom) on the limestone dissolution characteristics in a WFGD environment (Swart, personal communication, 2016). The South African limestone samples were received in 50kg bags. The limestone was crushed with a laboratory scale cone type crusher to a particle size of 45µm to coincide with WFGD conditions. To ensure the correct particle size distribution, a sieving process was followed using a 45µm sieve and laboratory shaker. The three South African samples were similarly split with a rotary splitter to obtain a homogenous sample of 250g each.

The 250g samples were placed in bags with identification, where a grab sample of approximately 150g were used for the gypsum synthesis, approximately 2g used for the XRF analysis and 1g used for QEMSCAN analysis.

4.2.2 FGD gypsum sampling and preparation

The FGD gypsum sample was sourced from EDF in Rybnik, Poland. The FGD gypsum is produced at the plant under WFGD conditions. The sample arrived in South Africa in a sealed 20kg bag. The gypsum sample was split with a rotary splitter to create a homogenous sample of approximately 250g. The 250g split sample was placed in a bag with identification. A grab sample of approximately 2g was used for XRF analysis, around 2g was used for QEMSCAN analysis and 5g was used for the TGA. The remaining sample was kept as a reference.

An analytical gypsum sample was used as a reference to determine the degree of purity. A 550g pure calcium sulphate dihydrate sample was obtained from Associated Chemical Enterprises (ACE). The batch number for the sample is 33876 with the control number 12912. A grab sample was used as a reference material for the XRF analysis and TGA.

4.3 GYPSUM SYNTHESIS FROM LIMESTONE

The Polish limestone and corresponding FGD gypsum samples were used as a reference to predict the quality of gypsum synthetically obtained in the laboratory.

Synthetic samples of gypsum were created by using the Polish limestone sample and sulphuric acid (H_2SO_4) in a one to one molar ratio. QEMSCAN analysis was used to determine resemblance of the created gypsum sample with the actual corresponding FGD sample. Thereafter the three South African limestone samples were used in a similar manner to create synthetic gypsum.

4.3.1 Experimental setup and procedure

The experimental procedure to manufacture gypsum in the laboratory was performed using basic chemistry molecular weight principles. A stoichiometric ratio of the reactants was used according to Equation 4.1, where the purity of the limestone and sulphuric acid was accounted for.

$$CaCO_{3(s)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(s)} + CO_{2(g)} + H_{2(g)} \quad \ldots\ldots balanced\ reaction \qquad (4.1)$$

WFGD conditions were simulated where a Ca/S ratio is normally just above 1 and the limestone will thus not convert completely.

The Polish limestone sample and sulphuric acid were placed in small glass beakers and weighed. The weighed limestone sample was placed into a solution with 1000ml water and continuously stirred by an overhead mechanical stirrer. The sulphuric acid was added to the limestone solution in 1.5ml increments at one minute intervals by using a small pipet. The last addition of sulphuric acid was performed by adding an additional 100ml of water to ensure the solution contained all of the acid.

The pH of the solution after adding the sulphuric acid was low (2 to 2.5). The pH was measured again after continuously stirring for two hours and it was found that the pH of the final solution was between 2.5 and 3. The low pH indicated that there was some unreacted sulphuric acid present in the solution, which can be attributed to impurities in the limestone not reacting or all the limestone molecules were not in contact with the sulphur. There will be small amounts of unreacted limestone and SO_2 gas in the industrial WFGD process, the difference is that the industrial process is continuous.

Two initial samples were prepared and left to react for 2 hours (Gypsum X) and 124 hours (Gypsum Y) respectively. Both of these samples were mechanically stirred for 2 hours with Gypsum X washed and filtered after the stirring period and Gypsum Y left for an additional 122 hours to react before washing and filtering. The pH of sample Y remained unchanged at a value between 2.5 and 3 before the filtering and washing process.

The gypsum product was in a solution of 1100ml water and for the first stage of the vacuum filtered process no additional water was added. After the first filtering session the wet gypsum product was put into a new solution with 750ml of water that acted as a mechanism to wash away the unreacted H_2SO_4. The pH of the new solution was measured and the filtering and washing process was repeated (again with 750ml of water) until the final solution measured a pH of between 6 and 9 to ensure the removal of unreacted sulphuric acid.

QEMSCAN analysis was used to determine which of the two final gypsum samples resembled the closest characteristics to the Polish FGD sample.

4.4 CHARACTERISATION AND ANALYSIS

Three different methods were used to determine the quality or purity of the created gypsum samples. QEMSCAN, XRF and TGA were used and results compared for each of the samples. QEMSCAN analysis was performed on samples A, C and K, and previously on the Polish gypsum and sample X. XRF analysis and TGA was performed on the Polish gypsum sample, sample A, C, K and X and additionally as a reference also an analytical gypsum sample.

4.4.1 Thermogravimetric analysis

As per the VGB 701 standard, thermogravimetric analysis allows for the evaluation of the change in sample weight subjected to a thermally controlled environment. It is recommended to analyse more than one of each sample to show repeatability. The degree of gypsum purity is measured from the content of released crystallisation water from the gypsum sample. The crystallisation water will be released from a moisture free sample between 40˚C and 360˚C. The initial TGA setup was done according to the temperature program shown in Table 4-1.

Table 4-1 Initial TGA setup

Heating Rate (˚C/min)	Final Temperature (˚C)	Atmosphere
9	920	N_2 gas @ 1.5 NL/min

Initial TGA runs were performed on the Polish gypsum, sample A, C and K. Equation 4.2 (as per the VGB 701 standard) was used to calculate the degree of purity:

$$Degree\ of\ Purity\ (\%) = \frac{KW\ .100}{20.93}\left(\frac{\%}{1}\right)\ldots \qquad (4.2)$$

$$where\ KW\ is\ the\ mass\ loss\ between\ 40℃\ and\ 360℃$$

It was found that only the Polish FGD gypsum sample provided credible results. The inherent moisture of the created samples was too high and the TGA did not provide reliable results.

This can be accredited to the formation of the gypsum in a solution in the laboratory compared to actual FGD gypsum formed in the FGD plant process. The setup delivered unrealistic results and it was decided to alter the temperature profile and keep the temperature constant at 80˚C for an hour to ensure a slower release of crystallisation water. The new temperature profile is shown in Figure 4-1.

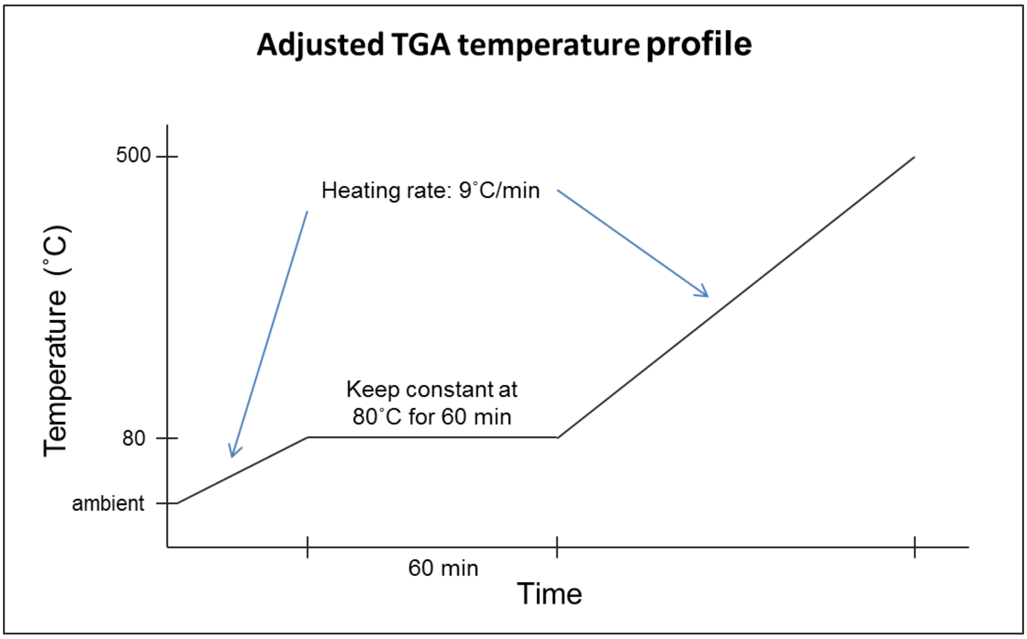


Figure 4-1 Adjusted TGA temperature profile

4.4.2 QEMSCAN

QEMSCAN analysis was performed on the limestone and gypsum samples at Eskom Research, Testing and Development Centre (Eskom RT&D). The analysis was done to determine the mineralogy of the samples by a method of fusing the samples in wax. The following sampling method was followed:

- Potting of wax:

  Teflon moulds were used to hold the waxed samples. The moulds were coated with silicone oil and dried in an oven for 30 minutes at 60˚C. The dried moulds were then filled with wax flakes and placed in a 120˚C oven for 20 minutes to ensure wax melting. The samples were added into the wax and stirred with a bamboo stick until well mixed. The samples were returned to the oven at 120˚C for 35 minutes to balance out the samples and temperatures. The temperature was lowered to 60˚C for 90 minutes to solidify the wax in the mould. After the 90 minutes the samples were removed and cooled at room temperature. The cooled samples were removed from the moulds and labelled.

- Polishing of samples and carbon coating:
  After the removal of samples from the moulds it is polished with a rotary polishing machine with water as lubricant. Five different polishing papers are used, varying in fineness and afterwards washed in soapy water. The completely dried samples were then carbon coated. The polished samples were placed in a carbon coating instrument where a thin layer of carbon was deposited on each sample.
- QEMSCAN instrument settings:
  A Field Emission Gun (FEG) QEMSCAN instrument was used. iMeasure software was used with the instrument during analysis with the settings shown in Table 4-2.

Table 4-2 QEMSCAN settings at Eskom RT&D.

QEMSCAN setting	Value
iMeasure version	5.4
QEMSCAN platform	FEG (Field emission
Accelerating voltage	20kV
Specimen current	-9.00nA
Beam optimisation	0.5
Working distance	13mm
BSE Background	16
Brightness	˜19
Contrast	˜94

The data output from the iMeasure software showed a list with all the minerals and a graphical representation of the sample. For the purpose of this document only the normalised list of minerals provided will be used. Graphical representations of the samples can be seen in the Appendix.

4.4.3 XRF

XRF analysis was performed on the various gypsum samples to determine the elemental analysis of each sample. The analysis was executed at the North West University Potchefstroom campus according to the standard fusion method. The following was used during the analysis:

- X-ray Flux: Type 67:33 (Lithium Tetraborate: Lithium Metaborate)
- PANalytical Axios Max X-ray machine
- PANalytical Eagon 2 Fusion instrument

The borate glass discs were prepared by mixing 6g of flux with 0.6g of sample, thus in a ratio of 1:10. The weighed and mixed flux and sample gets transferred into a 32mm crubicle. The crubicles were placed in an oven with a pre-set temperature of 1050˚C. The sample went through one heating cycle of 24 minutes. The oven transferred the melted sample to discs which were cooled. Cooling was delayed for 15 seconds and after the delay it went through a cooling cycle of 2 minutes. The cooled discs were placed from the casting dish onto a tray for analysis in the X-ray machine. The crubicles were cleaned between samples with a 10% citric acid solution in an ultrasonic bath and dried properly before the next sampling cycle. Elemental composition results obtained from the XRF analysis of the various samples were reported as oxides of the elements and represented as percentages of the total.

5. RESULTS AND DISCUSSION

5.1 INTRODUCTION

The results from limestone characterisation and gypsum quality results obtained from the three different analysis methods; QEMSCAN, TGA and XRF are shown in this chapter. The degree of purity for all three methods will be compared and discussed.

5.2 LIMESTONE CHARACTERISATION RESULTS

Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) analysis provided the data set on the results for the different limestone sources as shown in Table 5-1.

Table 5-1 Limestone samples QEMSCAN results.

	Polish Limestone	Limestone A	Limestone C	Limestone K
Carbonate: Calcite	97.1	92.2	72.2	40.7
Carbonate: Calcite (Siliceous)	1.6	2.6	18	33.6
Carbonate: Dolomite	0.1	4.1	1.6	15.9
Carbonate: Dolomite (Siliceous)	0.0	0.1	0.2	2.7
Carbonate: Ankerite	0.0	0.0	0.4	0.7
Gypsum	0.1	0.0	0	0.0
Feldspar	0.1	0.1	0.7	1.3
Sand: Quartz	0.9	0.5	6.1	4.5
Clay	0.0	0.0	0.4	0.1
Mica	0.1	0.2	0	0.2
Pyrite	0.0	0.1	0	0.0
Andalusite (Al Silicate)	0.0	0.0	0.1	0.0

The sum of the two calcite components are compared to the supplier specification, which is based on XRF analysis, and it shows similar purity results. The QEMSCAN results for limestone A gives 94.8% versus the 95% provided by the supplier, limestone C's QEMSCAN results shows 90.2% versus 90.8% and limestone K gives 74.3% versus a supplier provided quality of around 70%. The Polish limestone sample thus has a purity of 98.7%. A summary of the results can be seen in Table 5-2.

Table 5-2 Limestone QEMSCAN results vs. supplier specification.

	Polish Limestone	Limestone A	Limestone C	Limestone K
Pure calcite	97.1%	92.2%	72.2%	40.7%
Sum of pure + siliceous calcite	98.7%	94.8%	90.2%	74.3%
Supplier specification	95%+	95%	90.8%	+/-70%

5.3 GYPSUM CHARACTERISATION RESULTS

The synthetic gypsum production method in the laboratory was confirmed with QEMSCAN by evaluating the results obtained between the two reaction times from sample X and sample Y. The synthetic samples produced from the Polish limestone, limestone samples A, C and K and the Polish FGD gypsum were analysed with QEMSCAN. XRF analysis was performed on the four synthetic gypsum samples, the Polish FGD sample and as a reference an analytical sample. TGA was performed on the same six samples as the XRF analysis.

5.3.1 QEMSCAN

QEMSCAN analysis was used to determine which of the two final gypsum samples resembled the closest characteristics to the Polish FGD sample. Sample X was left for 2 hours to react and sample Y for 124 hours. It was found that the 2 hour sample (Gypsum X) provided closer characteristic results when the gypsum and siliceous gypsum combination when compared to the Polish gypsum. The QEMSCAN results are shown in Table 5-3, with the sum of the two components for the Polish FGD gypsum totalling 97.6% and for gypsum sample X 97.7%.

Table 5-3 Initial gypsum QEMSCAN results.

	Polish gypsum	**Gypsum X**	**Gypsum Y**
Carbonate: Calcite/Dolomite	1.3	0.5	0.0
Gypsum	97.5	96.9	99.4
Gypsum(Siliceous)	0.1	0.8	0.2
Gypsum(Clay)	0.7	0.4	0.2
Gypsum(P,K)	0.0	1.0	0.1
Sand: Quartz	0.3	0.4	0.1
Others	0.0	0.0	0.0

The method for creating Gypsum X in the laboratory was repeated by utilising the three South African limestone samples (A, C and K) to produce three gypsum samples that was analysed further. The three samples were created in the laboratory and must be noted that the samples produced from limestone C and K produced gypsum with a light beige colour, whilst the gypsum synthesised from limestone A produced a dark grey sample.

The QEMSCAN analysis results for the four synthetic samples and the Polish FGD gypsum sample are shown in Table 5-4. The four gypsum samples created in the laboratory showed small proportions of unreacted carbonate in relation to the actual FGD gypsum sample collected from Poland. This can possibly be attributed to the time available for reaction, which is longer in the laboratory than in the actual WFGD environment. The Polish FGD gypsum and gypsum sample A purity results corresponded very well with the limestone QEMSCAN analysis as shown in Table 5-1. The QEMSCAN results showed that the percentage of pure gypsum formed in sample C is a combination of the calcite and siliceous carbonate components in the limestone. Gypsum sample K showed a very high siliceous gypsum component when compared with the siliceous carbonate component in limestone sample K. Gypsum samples C and K also showed a higher proportion of impurities like sand.

Table 5-4 QEMSCAN analysis results for all gypsum samples.

	Polish gypsum	Gypsum X	Gypsum A	Gypsum C	Gypsum K
Carbonate: Calcite/Dolomite	1.3	0.5	0.0	0.1	0.0
Gypsum	97.5	96.9	95.9	91.3	22.6
Gypsum(Siliceous)	0.1	0.8	1.8	2.9	71.8
Gypsum(Clay)	0.7	0.4	0.7	2.2	2.4
Gypsum(P,K)	0.0	1.0	0.0	0	0.0
Feldspar: Albite	0.0	0.0	0.0	0.1	0.0
Feldspar: Microcline	0.0	0.0	0.0	0.1	0.0
Sand: Quartz	0.3	0.4	1.2	2.9	2.9
Clay: Kaolinite	0.0	0.0	0.0	0.3	0.1
Goethite (AlSi)	0.0	0.0	0.1	0.0	0.0
Others	0.0	0.0	0.2	0.2	0.2

5.3.2 TGA results

The adjusted temperature profile delivered similar results in calculating the degree of purity, where the original and adjusted temperature profile results can be seen inFigure 5-1. The Polish FGD gypsum sample was used as a reference sample during the analysis.

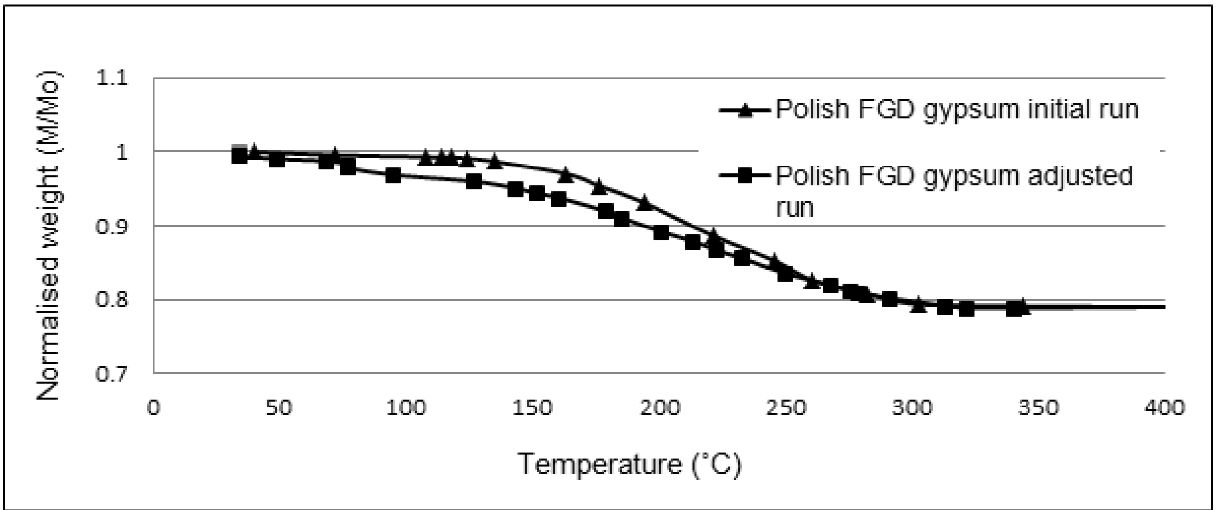


Figure 5-1 TGA: Initial Temperature vs. Adjusted Temperature Setup.

A graphical representation from the TGA results for the analytical gypsum sample can be seen in Figure 5-2. The graphical representation of the TGA results for gypsum sample A, C, K and X can be found in the Appendix.

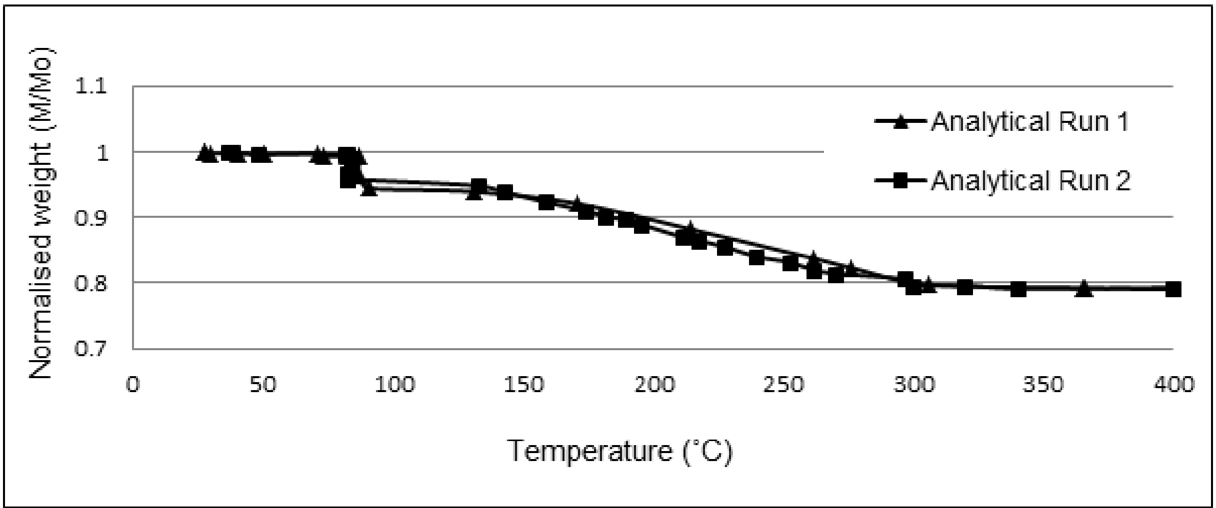


Figure 5-2 TGA: Analytical sample, run 1 and 2.

The six samples analysed with the TGA showed good repeatability and provided a sound indication of crystallisation water lost between 40˚C and 350˚C. Results obtained by using equation 4.2 to calculate the degree of purity can be seen in Table 5-5.

Table 5-5 Degree of Purity for gypsum samples based on TGA.

	Sample 1	**Sample 2**	**Average Degree of Purity**
Polish FGD gypsum	97.1%	96.7%	96.9%
Gypsum sample X	96.2%	95.5%	95.8%
Gypsum sample A	95.9%	95.9%	95.9%
Gypsum sample C	94.0%	94.6%	94.3%
Gypsum sample K	93.1%	94.1%	93.6%
Analytical gypsum sample	97.9%	99.7%	98.8%

5.3.3 XRF Results

XRF analysis was performed on six different samples. The results received were normalised on an LOI free basis. The next step was to normalise the results on an oxide free basis and the elemental analysis of each sample can be seen in Table 5-6. The raw results and calculations can be seen in the Appendix. As expected the two most prominent elements present in all of the samples are calcium and sulphur.

Table 5-6 Elemental analysis of all samples on an oxide free basis (normalised).

	Sample A	Sample C	Sample K	Sample X	Polish FGD gypsum	Analytical gypsum
Fe	0.058	0.272	0.551	0.011	0.028	0.065
Mn	0.019	0.029	0.048	0.016	0.014	0.000
Sr	0.000	0.000	0.000	0.000	0.000	0.037
Ba	0.000	0.000	0.000	0.210	0.000	0.000
Ti	0.007	0.045	0.136	0.000	0.042	0.015
Ca	56.513	57.405	53.548	57.424	59.053	56.691
K	0.040	0.040	0.025	0.021	0.017	0.022
S	42.218	37.292	37.538	41.656	40.320	42.253
P	0.000	0.000	0.005	0.005	0.007	0.006
Si	0.783	4.116	6.601	0.507	0.328	0.496
Al	0.305	0.627	1.281	0.124	0.162	0.238
Mg	0.041	0.149	0.263	0.013	0.000	0.081
Na	0.015	0.024	0.004	0.012	0.029	0.097

The purity based on the calcium and sulphur content according to the elemental analysis on an oxide free basis can be seen in Table 5-7.

Table 5-7 Degree of purity based on Ca & S elemental analysis (oxide free basis).

	Sample A	Sample C	Sample K	Sample X	Polish FGD gypsum	Analytical gypsum
Ca + S Purity	98.731	94.697	91.087	99.080	99.373	98.944
Total impurities	1.269	5.303	8.913	0.920	0.628	1.056

5.4 DISCUSSION

The quality and characteristics of the gypsum end product will ultimately dictate the application in the market. The quality of the FGD gypsum product is directly related to the quality of limestone used within the FGD process, and the purpose of the experiment was to try and determine to which extent.

Table 5-8 Summary of analysis method results.

	Sample A	Sample C	Sample K	Sample X	Polish FGD gypsum	Analytical gypsum
QEMSCAN (pure + siliceous gypsum)	97.7%	94.2%	94.4%	97.7%	97.6%	n/a
TGA	95.9%	94.3%	93.6%	95.8%	96.9%	98.8%
XRF elemental	98.7%	94.7%	91.1%	99.1%	99.4%	98.9%

A summary of the results obtained from QEMSCAN, TGA and XRF analysis can be seen in Table 5-8 and it shows the three methods provided results in close range. Samples K and X has variances of 3.3% whilst the variance with the analytical sample is only 0.1% between the TGA and XRF analysis. The results obtained from the three analysis methods for sample C are within a 0.5% range, thus providing the smallest standard deviation.

The results in Table 5-8 are compared with the limestone QEMSCAN results and supplier specifications in Table 5-2 and each sample can be discussed. The gypsum purity for all three analysis methods were above 95% for sample A, with the lowest value being 95.9%. The limestone purity as per the supplier specification was a guaranteed 95%+ and the QEMSCAN analysis showed a percentage of 94.8% (sum of pure and siliceous calcite). It shows by comparison that the gypsum purity for sample A is at least 1% higher than the limestone purity. Performing the same comparison for sample C shows a higher deviation in percentages of the analysis methods. The experimental results showed a difference in purity of almost 3% higher in the gypsum when the analysis results and the limestone purity as per supplier specification are compared. When comparing sample X and the Polish FGD gypsum analysis results with the limestone purity, it was found that the percentages correlates well and are in a close range. These two samples also showed that the expected gypsum purity can be slightly higher than the given limestone purity. The analysis of the analytical sample showed by means of the TGA and XRF that there are some errors associated with these two analysis methods. The purity of the analytical sample was supposed to be 100% but the analysis results indicate either a 1% error in analysis or 1% impurities in the sample.

Analysis results from gypsum sample K showed gypsum purity results that do not correlate well with the limestone purity if compared with the other samples. The limestone purity values in Table 5-2 is showed as 74.3% based on the QEMSCAN and around 70% as per supplier specification. The gypsum purity results as per the three analysis methods provided results ranging between 91.1% and 94.4%, which indicates a difference between the purities of more than 20%. The QEMSCAN analysis results of the limestone in Table 5-1 shows that there is a dolomitic carbonate compound of 19.3% present in the limestone sample. The difference in purity percentages can be represented by the reaction of the calcium in the dolomitic compound as well as the calcite compound of the limestone. Calcite reacts quickly with acids to form other components or CO_2, where dolomite is a harder and denser particle that takes longer to react. Dolomite may however react faster when in contact with a pure acid in low pH conditions. The experimental setup allowed for a low pH value because of the addition of a high concentrate sulphuric acid, thus creating conditions in the solution for not only the calcite to react but also the dolomite.

It was observed that the gypsum sample A had a dark grey colour whilst sample C and K resembled a beige colour similar to the Polish FGD gypsum sample

5.5 SUMMARY

Different limestone sources are tested at Eskom RT&D to determine if alternate sources will provide reliable results in the FGD process. The quality of the gypsum product will determine in which sector it may possibly be utilised. A Polish limestone and corresponding FGD gypsum sample was used as a base case in creating gypsum samples from three South African limestone samples synthetically in the laboratory. The aim of this exercise was to create gypsum samples that will replicate actual FGD gypsum samples from the WFGD process. The quality or purity of the gypsum samples were determined by TGA, QEMSCAN and XRF analysis. The three analysis methods provided results in a deviation not exceeding 3.3% per sample. It was found from gypsum samples A and C that the gypsum purity is a few percentages higher than the limestone purity. The lower quality limestone K delivered a gypsum sample that showed a high purity in the analysis. The unrealistic results obtained from the gypsum sample K is due to the experimental setup that allowed for a low pH in solution where the dolomitic compound of the limestone could also react.

Limestone A will produce gypsum with a quality of over 95%, making it suitable for use in all three major industries, namely wallboard, cement manufacturing and agriculture. The only possible problem that can be foreseen for this sample is the colour that is not near white.

Limestone C will have to be tested in the field under actual FGD conditions. The results showed gypsum purities very close to the 95% required for the wallboard industry, thus being definitely useful to the cement and agriculture industries.

The gypsum produced from Limestone sample K gave questionable results and more tests will have to be performed under a more constant pH to obtain realistic gypsum purity figures. Limestone K will however produce gypsum that will definitely work in the agricultural and possibly also the cement industry.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 OVERVIEW

The disposal of coal combustion products, which includes coal ash and the new combustion product Flue Gas Desulphurisation (FGD) gypsum, causes significant environmental and economic difficulties. Only a small fraction of the coal ash currently produced is used by other industries whilst the bulk of it is held in ash storage facilities. To reduce the environmental and economic impacts of the disposal of the coal ash and future FGD gypsum, alternative utilisation of these products was investigated.

The utilisation of fly ash and FGD gypsum was reviewed on a global scale. The proposed quality of FGD gypsum that can be expected from different South African limestone sources were also evaluated. Recommendations on industrial uses based on the quality spectrum of the gypsum samples are provided, as well as a bulk utilisation possibility of South African fly ashes when compared to ash samples from Poland. The way forward in terms of waste legislation barriers in South Africa was discussed.

6.2 CONCLUDING REMARKS

6.2.1 FGD Gypsum

Internationally FGD gypsum is used as a direct replacement for natural gypsum in the wallboard, construction and agriculture industries. Kusile power station will generate around 900 000 tonnes/annum of FGD gypsum when operated at full capacity. Gypsum use in the agricultural sector in South Africa is estimated at around 200 000 tonnes/annum, whilst the gypsum use in the cement manufacturing industry was estimated to be around 640 000 tonnes for the 2015 year. The combined demand between the agriculture and cement industries will be covered by the FGD gypsum produced from Kusile alone. The possibility of using FGD gypsum in the wallboard manufacturing industry remains, it is however very strict in terms of quality and other parameters. The quality of the limestone used in the FGD plant will have to be of a consistent good quality to deliver gypsum of that high standard.

The quality of the gypsum product will determine in which sector it may possibly be utilised. A Polish limestone and corresponding FGD gypsum sample was used as a base case in creating gypsum samples from three South African limestone samples synthetically in the laboratory. The aim of this exercise was to create gypsum samples that will replicate actual FGD gypsum samples from the WFGD process. The quality or purity of the gypsum samples was determined by TGA, QEMSCAN and XRF analysis. The three analysis methods provided results in a deviation not exceeding 3.3% per sample. It was found from gypsum samples A and C that the gypsum purity is a few percentages higher than the limestone purity. It was found that Limestone sample A, which had the highest quality, will most certainly deliver a consistent FGD gypsum product. With a purity exceeding 95%, a challenge may arise with regards to the colour for the use in the wallboard industry. The wallboard industry requires gypsum of a near-white colour, which is not the case in this sample. It is possible to bleach gypsum for colour removal, but the cost of this exercise is very high. The darker gypsum product can however be utilised in the industry by stakeholders that do not require a specific colour for aesthetic reasons.

If only the quality is considered it was found that gypsum sample A will most probably be suitable for the wallboard, cement and agriculture industry. Gypsum sample C showed results close to the 95% range required for use in all the industries. Further tests are required in a real WFGD environment to confirm the results. Gypsum sample K showed high quality gypsum in relation to the lower calcite values in the limestone, and it requires more testing in the industrial environment to confirm. Alternatively a laboratory setup can be used again, but with a change in pH parameters and residence time to closer simulate WFGD conditions.

6.2.2 Fly Ash

Early research shows that the use of fly ash in concrete has always been the single biggest end user (Manz, 1997). It is evident in the usage data provided by AQAA and ECOBA that the use of ashes in concrete and cement has always been the biggest end user where it accounts for almost two thirds of the total utilisation in these countries. Other areas of use for fly ashes includes the road construction and agriculture industries. Fly ash can for many reasons be seen as a resource, rather than a waste material. The placing of CCP's, in particular ash, as a fill in open cast mines can have environmental and social benefits.

South African coal consists of a very high ash content which in turn leads to vast amounts of coal ash generated annually. The 2015/2016 Eskom ash figures showed that 2.71 Mt of ash was recycled, and if the ash used internally as an effluent water sink is taken into account there was an additional 3.19Mt of ash available for use. Taking this into consideration it amounts to a maximum possible utilisation rate of about 18% or 5.8 Mt. Legislation pertaining to waste water possibly coming into effect in 2021 will most probably only impact Eskom's dry ashing stations, and water treatment plants will have to be installed. In turn this will result in more ash being available at these stations, creating the scenario of more fresh ash available for recycling.

Ash classification from samples in China, India, Australia and Turkey corresponds to the classification of South African samples, all of which show class F ashes with similar CaO percentages. Utilisation rates in India and China has risen dramatically over the last few years, mostly because of legislative changes and the acceptance of fly ash as a product that is widely used in different sectors, and not a waste.

Samples of ash from both Poland and South Africa was studied and compared to the South African legislation parameters. This comparison gave way to knowledge portraying that the fly ash from Poland and South Africa show strong similarities in terms of elemental composition and heavy metals. The ash samples from both countries can be classified as Class F ashes and classification of type for landfill disposal is Type 2 or 3 waste, depending on the leaching capabilities.

6.2.3 Legislation

The National Environmental Management: Waste Act (NEMWA) of 2008 facilitates the law responsible for waste management in enabling the protection of the environment and human health. In South Africa CCP's are classified as hazardous waste materials per the National Waste Information Regulations. This is based on the fact that it is a by-product of an industrial process.

A motivation may be submitted to the Minister of Environmental Affairs to list a specific activity as an activity that does not require a Waste Management Licence (WML) under Regulation 9 of GNR 634. The motivation must demonstrate that the waste management activity, which includes transport, handling and storage, can be performed consistently in a controlled manner to ensure no impact or risk on human health and the environment. An extensive list of information (as shown in GNR 634) is required to complete the requirements of the motivation.

South African products generated from the coal combustion process cannot be delisted as a waste, but if an application under Regulation 9 is approved no WML will be required for specific activities. The high cost of applying for a South African WML and coinciding strict norms and standards hinders smaller companies to utilise ashes at present and it can be similarly problematic for the FGD gypsum. By applying for a WML all waste monitoring, handling practises and procedures must be included. Results from laboratory projects and/or pilot studies should be included to demonstrate its impact on the environment.

A comparison was drawn between the legislation regulating CCP in both South Africa and the EU. This indicated that South African waste classification practises are much stricter in the current time and perhaps in environmental legislation terms a few years behind. The classification of CCP's in South Africa hinders the development of products and the utilisation thereof. The classification of EU CCP's as by products enables the utilisation of it in a bigger spectrum of applications.

In late 2016, Eskom submitted an application under Regulation 9 to the DEA for the activities of brick making, road construction, mine backfilling and agriculture to be approved as activities that do not require WML's in utilising specifically fly ash. A similar application will follow when stable samples of FGD gypsum are produced at Kusile power station and the characteristics of the end product is more certain.

New legislation, gazetted in June 2017, proposed the exclusion of certain waste streams from the definition of waste in NEMWA (2008). Comments were requested and Norms and Standards must be developed to ensure the safety of the environment and human health when these materials may be used in products.

6.3 RECOMMENDATIONS

6.3.1 FGD Gypsum

When the first FGD is in commercial operation samples of FGD gypsum product will be available for thorough testing to determine the classification as per SANS 10234. As soon as the results of classification become available, Eskom can apply for a WML and lodge a Regulation 9 application for specific applications of FGD gypsum utilisation. The FGD gypsum quality and full set of specifications must be defined to determine commercial strategies. Off takers can then be identified and infrastructure must be implemented on site to ensure safe and easy logistical solutions for end users. The final step in the life cycle will be the implementation of commercial contracts for the FGD gypsum end product.

Markets will be available for the utilisation of the FGD gypsum end product if all the quality criteria can be met, which is not only based on the gypsum purity. The legislation barrier will have to be overcome as soon as commercial FGD gypsum becomes available for testing to ensure minimal storage of a valuable product.

6.3.2 Fly Ash

The South African legislative framework inhibits the use of coal ash to a major extent due to the classification of the material as a hazardous waste. South African ashes are used by a few different companies within the country, but evidence will have to be provided in terms of the safety of the products to unlock and stimulate more markets. Bulk utilisation possibilities, which will mainly include the mining and agricultural sectors in South Africa, will have to be approached with technologies that provide a safe alternative for natural products.

Eskom has cost-plus contracts in place with mines at some of the power stations. These contracts indicate a shared responsibility in terms of environmental compliance and the ensuring of rehabilitation when the mines are closed. Bulk volumes of ash can be used as a filler in the mines, in AMD treatment and as soil amelioration in the rehabilitation process. The use of ashes in mining in South Africa will have to be researched extensively with pilot studies. Pilot studies will have to be conducted under the supervision of DEA to show that there is no harmful effect on human health or the environment. South Africa is a water scarce country, and concerns regarding the water safety will have to be properly addressed with well executed plans in relation to water monitoring before, during and after these studies and implementation of future projects.

The South African ashes compare well with the ashes from Poland, and if the legislative barriers can be overcome it can be used in the same industries with great success. South Africa and in specific Eskom can use the Indian ash industry as inspiration. By changing the legislation pertaining to the use of ash in the construction industry, the utilisation rates of ash was around 56% in 2015. Indian ash is also of a low grade and high ash content ranging between 30% and 45%, and a total production of ash annually six times higher than in South Africa.

It is highly recommended to consider the scenario in Eskom pertaining to the change in legislation, where ashes are given away and not sold. Cost savings in terms of future dumps, costly liners, operating and capital expenditure can possibly outweigh the need to sell lower volumes of ash.

6.3.3 Low Cost Housing

A condition related to the postponement of compliance to air quality legislation stated that Eskom must get involved in offset intervention projects. The improvement of thermal and energy efficiency in low cost housing units will address human health issues and finally offset pollution.

The current low cost housing situation in South Africa includes structures that provide protection against basic weather elements with minimal thermal efficiency. The problem of thermal efficiency can be addressed by using CCP's as construction materials. The study by Çiçek & Çinçin (2015) showed that Turkish fly ash is similar to South African fly ash, and the real size brick manufactured from 88% fly ash and 12% lime in an autoclave were mechanically and thermally sound. The exact same method used by them can be applied in a South African context with great success considering the approved section 74 application for brick manufacturing.

The study by Li, J. et al. (2015) showed that the combination of fly ash and FGD gypsum in the manufacturing of fire resistant panels showed positive results in terms of insulation and mechanical properties. As soon as FGD gypsum becomes commercially available in South Africa and the legislation hurdles have been overcome, manufacturing sites can produce similar panels on Eskom grounds and use it as ceiling or inside wall panels in low cost housing units.

Global utilisation strategies cannot be implemented without considering South African legislation, high transport costs and a lack of proper infrastructure, additional capital and operational expenditure and stakeholder engagement. A significant challenge faced in the long term will be a stakeholder paradigm shift. This paradigm shift will be imperative to create a platform for the implementation of such an innovative solution.

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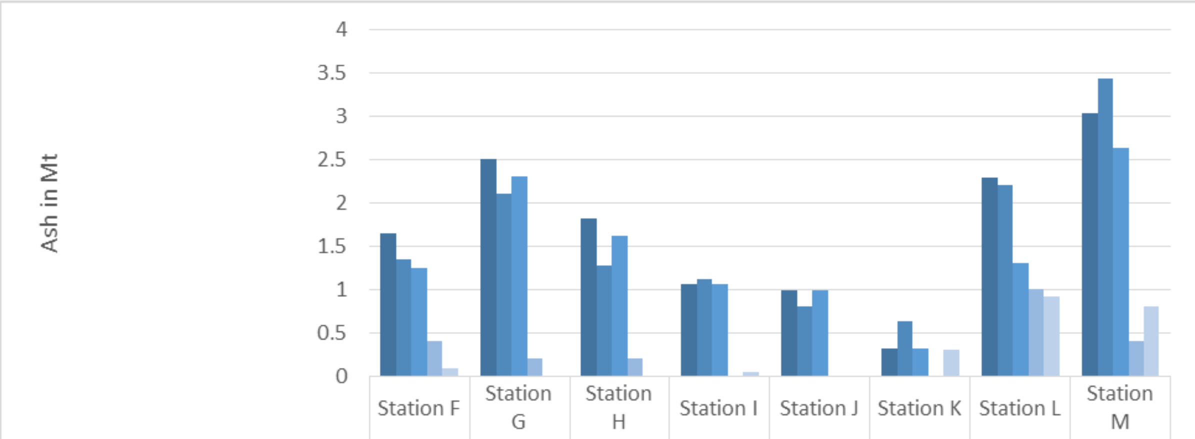
8. APPENDIX

Table 8-1 Ash available at wet ashing stations.



	Station F	Station G	Station H	Station I	Station J	Station K	Station L	Station M
Ash Produced (Mt): 2011/2012	1.65	2.506	1.824	1.068	0.996	0.324	2.302	3.04
Ash produced (Mt): 2015/2016	1.347	2.113	1.286	1.117	0.807	0.628	2.216	3.44
Ash used for effluent sink (Mt)	1.25	2.306	1.624	1.068	0.996	0.324	1.302	2.64
Saleable (Mt): 2011/2012	0.4	0.2	0.2	0	0	0	1	0.4
Saleable (Mt): 2015/2016	0.097	0	0	0.049	0	0.304	0.914	0.8

TGA analysis results can be found in Figure 8-1, Figure 8-2, Figure 8-3, Figure 8-4 and Figure 8-5.

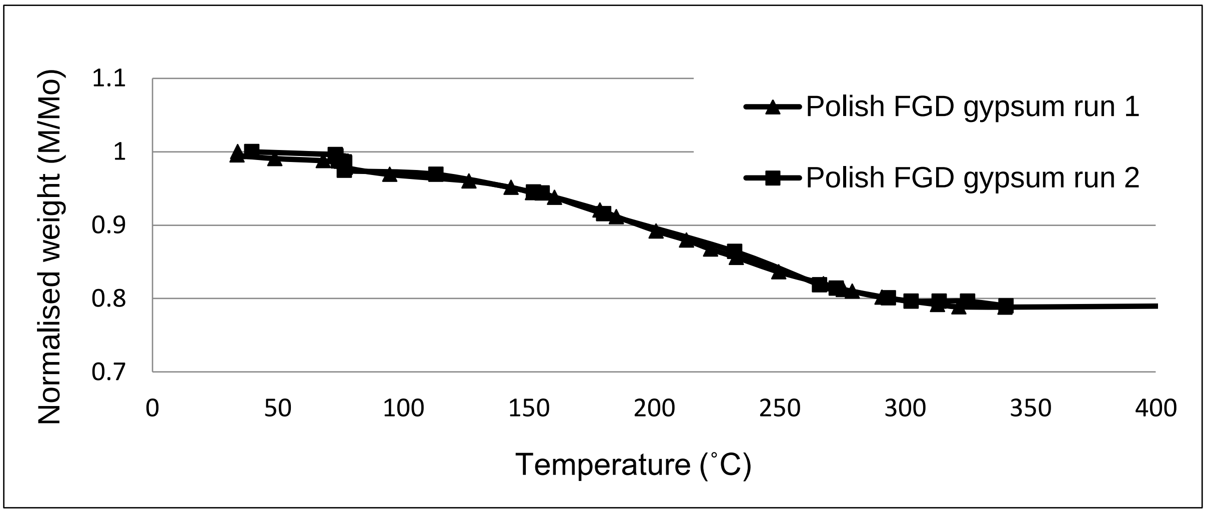


Figure 8-1 TGA: Polish FGD gypsum sample results.

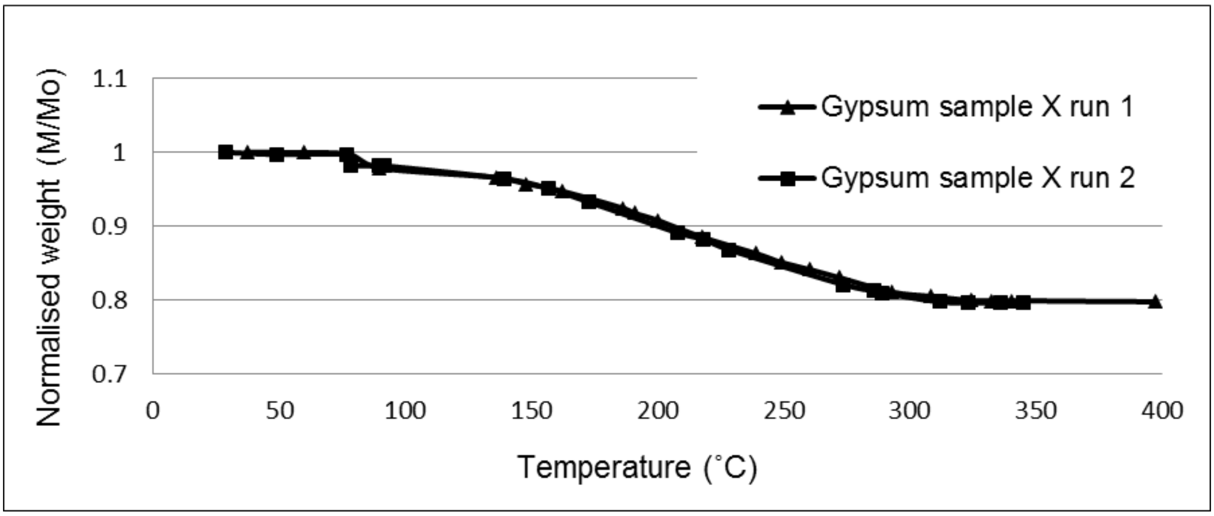


Figure 8-2 TGA: gypsum sample X, run 1 and 2.

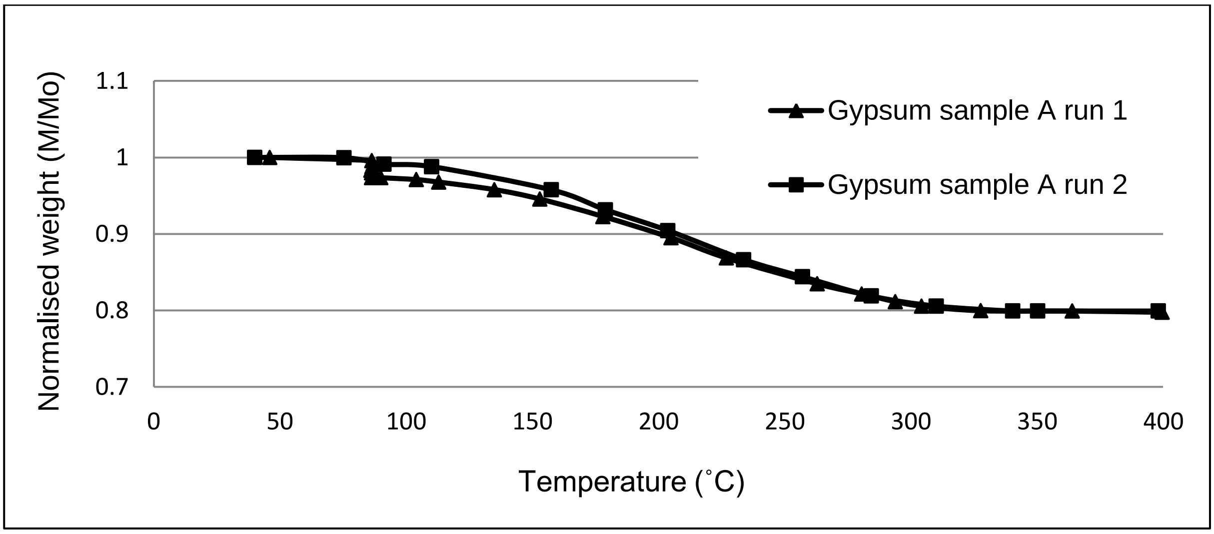


Figure 8-3 TGA: gypsum sample A, run 1 and 2.

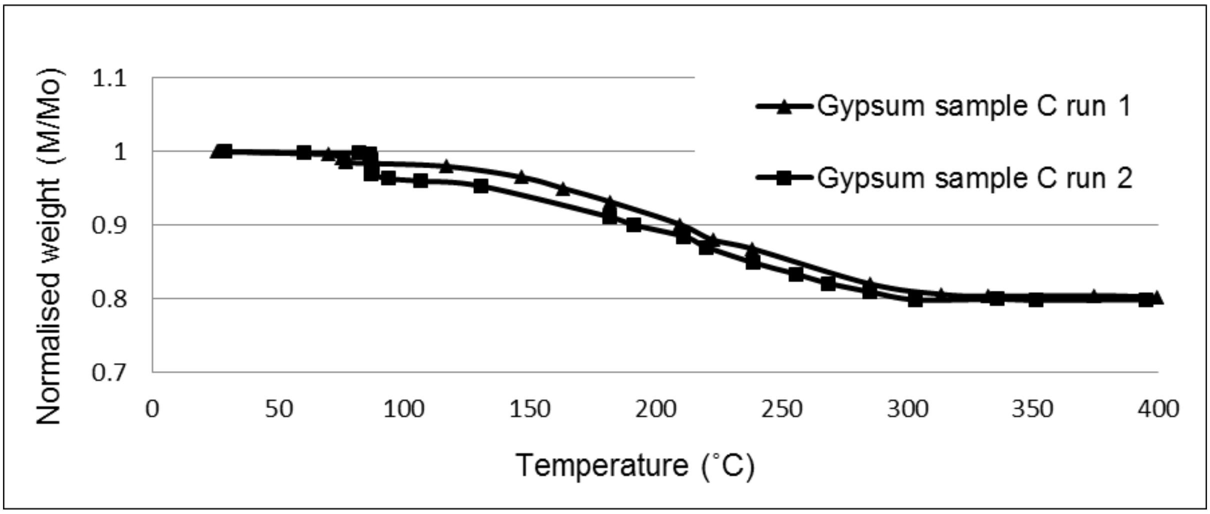


Figure 8-4 TGA: gypsum sample C, run 1 and 2.

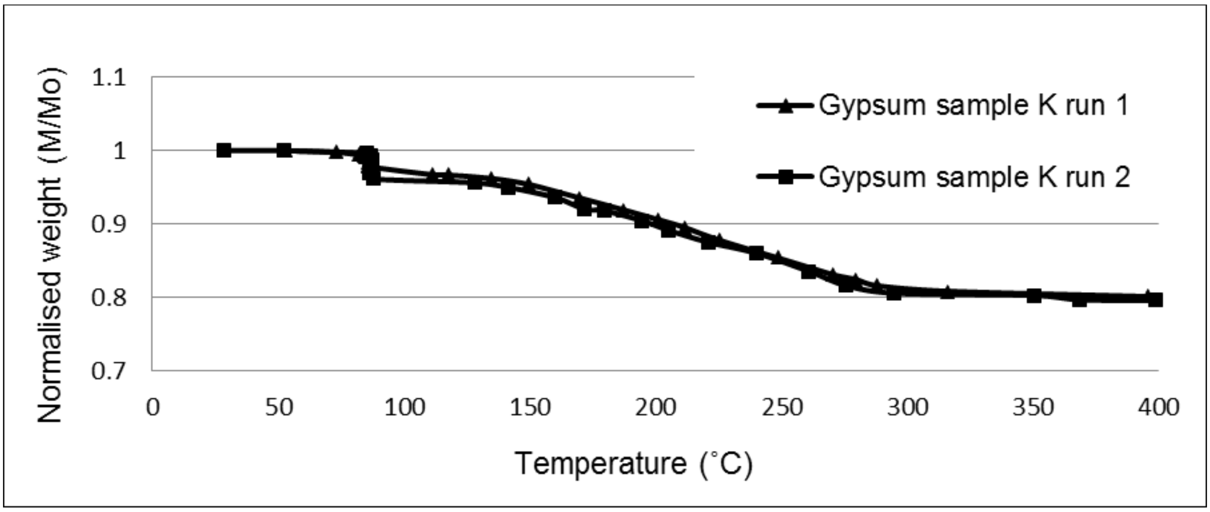


Figure 8-5 TGA: gypsum sample K, run 1 and 2.

The XRF analysis tables and calculations can be seen in Table 8-2, Table 8-3, Table 8-4 and Table 8-5. The concluded purities of all samples is showed in Table 5-7.

Table 8-2 XRF analysis of all gypsum samples.

	Gypsum from Limestone Sample A	Gypsum from Limestone Sample C	Gypsum from Limestone Sample K	Gypsum from Polish Limestone X	Polish FGD gypsum (1)	Polish FGD gypsum (2)	Analytical Calcium Sulphate Hemi Ca2SO4.2H2O
Total sum (%)	85.10	91.71	90.17	95.61	93.15	95.42	93.73
Sum Majo (%)	63.336	63.581	65.398	66.675	66.48	66.648	68.493
Fe2O3 (%)	0.056	0.268	0.549	0.011	0.03	0.084	0.068
Mn3O4 (%)	0.009	0.014	0.023	0.008	0.007	0.000	0.000
SrO (%)						0.088	0.016
BaO (%)				0.084	0	0.000	0.000
TiO2 (%)	0.004	0.026	0.079		0.03	0.013	0.009
CaO (%)	26.763	27.65	26.122	28.791	29.76	27.546	29.070
K2O (%)	0.033	0.033	0.021	0.018	0.02	0.015	0.019
SO3 (%)	35.679	32.055	32.679	37.272	36.26	37.382	38.665
P2O5 (%)			0.004	0.004	0.01	0.006	0.005
SiO2 (%)	0.567	3.031	4.923	0.389	0.25	0.807	0.389
Al2O3 (%)	0.195	0.408	0.844	0.084	0.11	0.270	0.165
MgO (%)	0.023	0.085	0.152	0.008	0.00	0.399	0.049
Na2O (%)	0.007	0.011	0.002	0.006	0.01	0.036	0.048
LOI (%)	21.48	27.82	24.39	28.57	26.67	28.740	25.200
Trace elements	0.2887	0.3042	0.378	0.3631	n/a	0.035	0.036

Table 8-3 Elemental analysis on an oxide free basis.

	Gypsum from Limestone Sample A	Gypsum from Limestone Sample C	Gypsum from Limestone Sample K	Gypsum from Polish Limestone X	Polish FGD gypsum (1)	Polish FGD gypsum (2)	Analytical Calcium Sulphate Hemi Ca2SO4. 2H2O
Fe	0.031	0.147	0.294	0.006	0.015	0.044	0.035
Mn	0.010	0.016	0.025	0.009	0.008	0.000	0.000
Sr	0.000	0.000	0.000	0.000	0.000	0.112	0.020
Ba	0.000	0.000	0.000	0.113	0.000	0.000	0.000
Ti	0.004	0.025	0.072	0.000	0.023	0.012	0.008
Ca	30.200	31.080	28.547	30.861	31.993	29.539	30.333
K	0.022	0.022	0.013	0.011	0.009	0.009	0.012
S	22.560	20.191	20.012	22.387	21.844	22.463	22.608
P	0.000	0.000	0.003	0.003	0.004	0.004	0.003
Si	0.418	2.228	3.519	0.273	0.178	0.566	0.265
Al	0.163	0.340	0.683	0.067	0.088	0.214	0.127
Mg	0.022	0.081	0.140	0.007	0.000	0.361	0.043
Na	0.008	0.013	0.002	0.007	0.016	0.040	0.052
Sum:	53.438	54.142	53.311	53.743	54.177	53.363	53.506

Table 8-4 XRF elemental analysis on an oxide free basis - normalised.

	Gypsum from Limestone Sample A	Gypsum from Limestone Sample C	Gypsum from Limestone Sample K	Gypsum from Polish Limestone X	Polish FGD gypsum (1)	Polish FGD gypsum (2)	Analytical Calcium Sulphate Hemi Ca2SO4. 2H2O
Fe	0.058	0.272	0.551	0.011	0.028	0.083	0.065
Mn	0.019	0.029	0.048	0.016	0.014	0.000	0.000
Sr	0.000	0.000	0.000	0.000	0.000	0.209	0.037
Ba	0.000	0.000	0.000	0.210	0.000	0.000	0.000
Ti	0.007	0.045	0.136	0.000	0.042	0.022	0.015
Ca	56.513	57.405	53.548	57.424	59.053	55.354	56.691
K	0.040	0.040	0.025	0.021	0.017	0.018	0.022
S	42.218	37.292	37.538	41.656	40.320	42.094	42.253
P	0.000	0.000	0.005	0.005	0.007	0.007	0.006
Si	0.783	4.116	6.601	0.507	0.328	1.061	0.496
Al	0.305	0.627	1.281	0.124	0.162	0.402	0.238
Mg	0.041	0.149	0.263	0.013	0.000	0.677	0.081
Na	0.015	0.024	0.004	0.012	0.029	0.075	0.097

Table 8-5 Calculations to determine calcium and sulphur content to determine gypsum purity.

	Gypsum from Limestone Sample A	Gypsum from Limestone Sample C	Gypsum from Limestone Sample K	Gypsum from Polish Limestone X	Polish FGD gypsum (1)	Polish FGD gypsum (2)	Analytical Calcium Sulphate Dihydrate Ca2SO4.2H2O		
Ca/S molar ratio								**Pure**	
Ca	1.410	1.432	1.336	1.433	1.473	1.381	1.415	1	
Ca (corrected)	1.314	1.334	1.245	1.335	1.373	1.287	1.318	1	
S	1.317	1.163	1.171	1.299	1.257	1.313	1.318	1	
Ca/S	1.071	1.232	1.141	1.103	1.172	1.052	1.073	1	Applied as correction factor
Ca/S (corrected)	0.998	1.147	1.063	1.027	1.092	0.980	1.000	1	

Purity based on Ca & S content in pure, dehydrated CaSO4 on an oxide-free basis (Ref. to blue table)							
from S	95.0	83.9	84.5	93.7	90.7	94.7	95.1
from Ca	101.7%	103.3%	96.4%	103.4%	106.3%	99.6%	102.0%
from Ca (corrected)	94.8%	96.3%	89.8%	96.3%	99.0%	92.8%	95.1%

Ca+S Purity	98.73	94.70	91.09	99.08	99.37	97.45	98.94
Total impurities	1.25	5.27	8.87	0.90	0.61	2.55	1.06

wt.% Ca & S in 1 mol pure, dehydrated CaSO4 on an oxide-free basis

Element	mass in g	wt.%
Ca	40.078	55.55
S	32.065	44.45
	72.143	72.143

Pure Ca/S weigth ratio	1.250
Analytical CaSO4 Ca/S ratio	1.342
Correction factor on mass basis	1.073