SOUTH AFRICA CLASS F FLY ASH FOR ROADS: PHYSICAL AND CHEMICAL ANALYSIS

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Abstract

Fly Ash is a by-product at thermal power stations, also otherwise known as residues of fine particles that rise with flue gases. An industrial by-product may be inferior to the traditional materials used construction applications, but, the lower the cost of these inferior materials make it an attractive alternative if adequate performance can be achieved. The objective of this study is to evaluate the chemical and physical effectiveness of self-cementing fly ashes derived from thermal power stations for construction applications with combined standards. Using laboratory testing specimens, suitable types of Fly Ashes namely: Kendal Dump Ash, Durapozz and Pozzfill, were tested to the required standards to evaluate the potential properties. All three Fly Ashes have been classified as a Class F Fly Ash, which requires a cementing agent for reactions to take place and for early strength gains in the early stages of the reaction processes. The Fly Ashes conformed to the combination of standards and have shown that the proper reactions will take place and will continue over period of time. The use of fly ash is accepted worldwide due to saving in cement, consuming industrial waste and making durable materials, especially due to improvement in the quality fly ash products.

Keywords: Class F Fly Ash, Pozzolanic Reaction, Physical characteristics, Chemical Characteristics, Standards

1. INTRODUCTION

Fly Ash is a by-product at thermal power stations, also otherwise known as residues of fine particles that rise with flue gases. Fly Ash solidifies while suspended in exhaust gases and is collected by electrostatic precipitators or filter bags. Fly Ash as defined by the South African Bureau of Standards (SABS) (SABS, 2002) as a powdery residue obtained by the separation of the solids from the flue gases during combustion of pulverized released from combustion of coal, 80% of the solid residue released from combustion of coal is released as Fly Ash.

South Africa only produces Class F Fly Ash but it was proved in studies around the world that due to that, it's a pozzolanic material; it reacts with lime/cement to form cementitous compounds (Guyer, 2011). Fly Ash is pozzolanic in both Class C and Class F Fly Ash. The reaction that occurs when Fly Ash is mixed with cement and water, sets free calcium hydroxide ($Ca(OH)_2$) but instead of going to waste, the $Ca(OH)_2$ combines with Fly Ash to form additional hydrate compounds.

This reaction is known as pozzolanic reaction (Mehta, 1998). The Fly Ash mixtures in concrete have reduce proportion of sand used, reduction in amount of water and due to that Fly Ash has a lower density than cement, produces higher volume of cementitious paste (Ash Resources). South Africa has abundant of Fly Ash resources and processed for other commercial uses in South Africa but mostly processed for the use in concrete mixes. For the purpose of this study, three types of Fly Ashes have been sourced from Kendal power station and Lethabo Power station respectively. Two of the Fly Ashes are processed and one type is directly sourced from the Ash dump at Kendal power station. The three Fly Ashes selected are namely:

1. DURAPOZZ – processed Fly Ash from Lethabo power station
2. POZZFILL – processed Fly Ash from Kendal power station
3. Dump Ash – directly sampled from the Ash Dumps at Kendal power station

The choice of these Fly Ashes is due to that it is the Fly Ash mostly used for cement making and is readily available for supplier.

2. SOUTH AFRICA STANDARDS

There are currently no specified standards for the use of Fly Ash as a soil stabilizer in South Africa. The standards that are utilized, and is intensively used, is for the determination of the properties of the Fly Ash to be utilized as an additive in cement production(C&CI, 1998). It is in this study that the current standards are used to analyze the properties of the Fly Ash for the suitable use as a soil stabilizer (COLTO, 1998; TMH1, 1986). In combination with current stabilization standards, documentation will be provided for designers to follow as a guideline for soil stabilization with Fly Ash. The current SANS methods developed for Fly Ash analyzing will be used which also correlates with British Standards that are also still followed today. Compliance with various requirements assures the user that unsuitable Fly Ash is not being used for works. The following main standards will be used to evaluate the physical and chemical properties of the three (3) individual Fly Ashes obtained for this study:

1. SANS 1491-2 (2005)
2. SANS 50196-1(2006)
3. SANS 50197-1 (2009)
4. BS3892-1,2 (1997)

Within the standards, as mentioned above, other specification tests are also conducted which contributes to the whole of the SANS1491-2 and SANS 50197-1. The Fly Ash results is compared to the set specifications as mentioned and each of the Fly Ashes in this study is approached separately. The test results of the Fly Ashes can be used to evaluate the following cases:

1. Classification of the Fly Ash by using results from the XRF analysis.
2. Evaluate the cementing potential
3. Evaluate the pozzolanic reaction time to predict whether the reaction will continue for a long period of time.
4. Determine the Loss Of Ignition (LOI) for strength evaluation
5. Determine of Sulphur content (SO_3) for the formation of ettringite
6. Determine the amount of free lime (fCaO) for activation of carbonation
7. Analyse total amount of Sodium (NA_2O), Magnesium (MgO) and Calcium (CaO), which contributes to higher strengths.

3. MATERIALS AND TESTING

3.1 DURAPOZZ

DURAPOZZ is an international recognized high quality Fly Ash. DURAPOZZ is mostly used for concrete mixes where it contributes to a reduced carbon dioxide (CO_2) footprint. DURAPOZZ is spherical in particle shape, fine particle size and has pozzolanic reactivity (Ash Resources). Tables 1 and 2 show the results for compliance to SANS 50197-1.

Tables 3 and 4 show the XRF analysis and weekly sampling checks completed. All the parameters of the test results shows that the Lethabo DURAPOZZ Fly Ash complies with SANS1491-2 (2005) and with SANS 50197-1. The compliance with SANS 50197-1 also shows that it can be used as a constituent in cement. The total CaO (TCaO) is not reactive Cao (RCaO). If TCaO is less than 10%, then the RCaO is definitely less than 10%.

Table 1 DURAPOZZ test results according to Specifications

Method	Description	Specification	Results
EN196-2	LOI	<5.0	0.46
EN196-2	LOI	<5.0	0.88
EN196-2	Sulpur content	<2.5	0.03
EN451-1	FCaO	<1	0.08
EN196-21	Total Alkalies	<5	0.11
EN451-2	Finess	<40	11.47
SANS6157	Finess	<12.5	10.8

Table 2 DURAPOZZ test results according to Specifications

Additional restrictions			
Method	**Description**	**Specification**	**Results**
EN197-1	RSiO2	>25	36.6
EN197-1	RCaO	<10	4.68

3.2 POZZFILL

POZZFILL does not conform to the requirements of SANS 1491-2 (2005). POZZFILL is extensively used as a reactive cementitious filler in South Africa. The unique combination enables the product to import significant features and benefits in cementitious binder (Ash Resources). POZZFILL for this study was sourced from Kendal power station. POZZFILL is also proven in road subbase, asphalt and refractory applications. Tables 5 and 6 show the results for compliance to SANS 50197-1. Table 7 show the XRF analysis while Table 8 shows the weekly sampling test report. Kendal POZZFILL Fly Ash evaluated herein the test results, complies with SANS 50197-1

Table 3. XRF Analysis of the DURAPOZZ Fly Ash

Parameter	Unit	Result
SiO_2	(%)	54.28
Al_2O_3	(%)	34.14
Fe_2O_3	(%)	3.46
CaO	(%)	4.12
MgO	(%)	1.08
K_2O	(%)	0.57
Na_2O	(%)	0.11
TiO_2	(%)	1.59
Mn_2O_3	(%)	0.04
P_2O_5	(%)	0.64
Cr_2O_3	(%)	0.01
SrO	(%)	0.12
ZnO	(%)	0
SO_3	(%)	0.03
LOI	(%)	0.46
CaO/SiO_2	ratio	0.08
$SiO_2 + Al_2O_3+Fe_2O_3$		91.88

Table 4 weekly sampling test results of the DURAPOZZ Fly Ash

Day	Date	% Retained on a 45µm sieve (Wet)	% LOI
		Standard: Max: 12.5% (SANS 1491:2)	**Standard: Max:5.0% (SANS 1491:2)**
Sunday	15-Jul-12	9.70%	0.55%
Monday	16-Jul-12	9.90%	0.60%
Tuesday	17-Jul-12	9.80%	0.53%
Wednesday	18-Jul-12	10.80%	0.49%
Thursday	19-Jul-12	11.10%	0.72%
Friday	20-Jul-12	10.30%	0.63%
Saturday	21-Jul-12	9.80%	0.59%

Table 5 POZZFILL test results

Method	Description	Specification	Results
EN196-2	LOI	<5.0	2.81
EN196-2	LOI	<5.0	1.02
EN451-1	FCaO	<1	0.28
EN451-2	Finess	<40	44.5
SANS6157	Finess	<12.5	44.33

Table 6 POZZFILL test results

Additional restrictions			
Method	**Description**	**Specification**	**Results**
EN197-1	RSiO2	>25	34.55
EN197-1	RCaO	<10	5.38

Table 7 XRF Analysis of the POZZFILL Fly Ash

Parameter	Unit	Result
SiO_2	(%)	52.16
Al_2O_3	(%)	30.99
Fe_2O_3	(%)	3.62
CaO	(%)	5.16
MgO	(%)	1.62
K_2O	(%)	0.73
Na_2O	(%)	0.35
TiO_2	(%)	1.62
Mn_2O_3	(%)	0.04
P_2O_5	(%)	0.6
Cr_2O_3	(%)	0
SrO	(%)	0.18
ZnO	(%)	0.001
SO_3	(%)	0
LOI	(%)	2.81
CaO/SiO_2	ratio	0.10
$SiO_2 + Al_2O_3 + Fe_2O_3$		86.77

Table 8 Weekly sample report

Day	Date	% Retained on a 45µm sieve (Wet)	% LOI
		Standard: Max: 12.5% (SANS 1491:2)	**Standard: Max: 5.0% (SANS 1491:2)**
Sunday	15-Jul-12	33.40%	0.52%
Monday	16-Jul-12	35.20%	0.67%
Tuesday	17-Jul-12	35%	0.53%
Wednesday	18-Jul-12	32.90%	0.63%
Thursday	19-Jul-12	32%	0.55%
Friday	20-Jul-12	34.80%	0.62%
Saturday	21-Jul-12	33.30%	0.57%

4. KENDAL DUMP ASH

Apart from DURAPOZZ and POZZFILL, an untreated samples was taken directly from the landfill dumpsites at Kendal power station. This particular Fly Ash is processed further to produce Ash Resources' products such as POZZFILL. The dump Fly Ash does not comply to SANS 1491-2 but to compare the three Fly Ashes, test data was also completed.
Table 9 shows the results for the XRF Analysis while Table 10 shows the LOI in combination with the weekly sampling report.

Table 9 XRF Analysis of the Kendal Dump Ash

Parameter	Unit	Result
SiO_2	(%)	52.16
Al_2O_3	(%)	30.99
Fe_2O_3	(%)	3.62
CaO	(%)	5.16
MgO	(%)	1.62
K_2O	(%)	0.04
Na_2O	(%)	0.6
TiO_2	(%)	0
Mn_2O_3	(%)	0.18
P_2O_5	(%)	0.6
Cr_2O_3	(%)	0
SrO	(%)	0.18
ZnO	(%)	0.001
SO_3	(%)	0
LOI	(%)	2.81
CaO/SiO_2	ratio	0.10
$SiO_2 + Al_2O_3+Fe_2O_3$		86.77

Table 10 Weekly sampling test results for Kendal Dump Ash

Day	Date	% Retained on a 45µm sieve (Wet)	% LOI
		Standard: Max: 12.5% (SANS 1491:2)	**Standard: Max:5.0% (SANS 1491:2)**
Sunday	15-Jul-12	48.3%	0.97%
Monday	16-Jul-12	27.9%	1.58%
Tuesday	17-Jul-12	42.0%	1.17%
Wednesday	18-Jul-12	43.5%	0.86%
Thursday	19-Jul-12	29.7%	1.40%
Friday	20-Jul-12	33.8%	0.99%
Saturday	21-Jul-12	Plant Closed	Plant Closed

Grading Analysis

	Min	Max	Lab Number :					
SIEVE	Spec	Spec	Kendal	Durapozz	Pozzfill			
3.350			100					
2.360			98					
1.180			94					
0.600			90					
0.425			86					
0.300			81	100	100			
0.150			64	99	96			
0.075			47	96	87			
0.060			40	77	68			
0.050			36	73	63			
0.020			21	54	37			
0.005			7	2	2			
0.002			1	1	1			

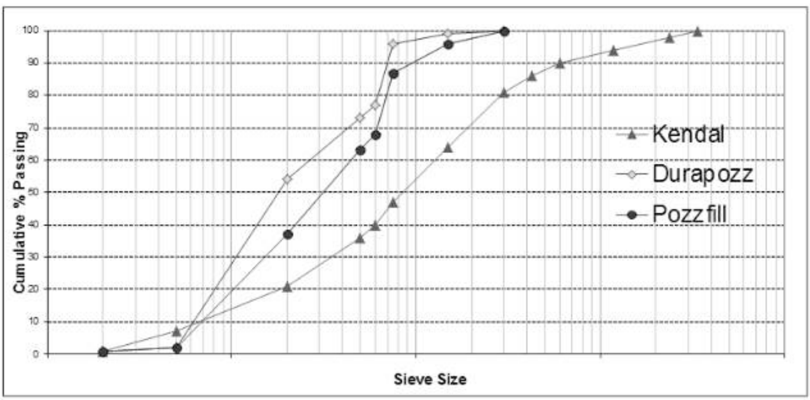

Figure 1 size distribution curves of Fly Ash

5. ANALYSIS AND DISCUSSION

Chemical characteristics

The silica (SiO_2) forms stable cementitious compounds in reaction with $Ca(OH_2)$ and with addition of water, the pozzolanic reaction will continue for a considerable period of time. The high percentage of SiO_2 shown in tables 3, 7, 9 confirms that all three Fly Ash samples for this study will continue with the reaction process. The CaO/SiO_2 ratio, which is indicative of cementing potential, varies between 0.08 for the DURAPOZZ in table 3 and 0.1 for the POZZFILL and Kendal Dump Ash respectively as shown in table 7, 9. All three Fly Ash specimens show a low cementing potential therefore a cementing agent will be required during any stabilization project. A study completed by Ojo (2010), made a distinction between Class C and Class F Fly Ash according to their aggregate Alumina, Silica and Ferric Oxide contents. Distinction is made on the sum of the total aggregate Alumina (Al_2O_3), Silica (SiO_2) and Feric Oxide (Fe_2O_3) and is presented in the following formulae:

$SiO_2 + Al_2O_3 + Fe_2O_3$

If the sum is greater than 70%, then the Fly Ash is classified as Class F and if the sum is between 50% - 70%, it is classified as a Class C. In the tables 3, 7 and 9, it shows that all three Fly Ashes fall in the range of Class F Fly Ash.

The LOI is a measurement of unburned coal remaining in the Ash and is critical characteristic of Fly Ash. In concrete, for instance, high carbon levels, type of carbon, the interaction of soluble ions in Fly Ash can result is significant air entrainment problems in fresh concrete and can affect the durability of concrete. LOI is low on all three Fly Ashes as shown in tables 1, 3 and 4 varied from 0.46 to 0.88. POZZFILL in tables 5, 7 and 8 varied from 0.52 to 2.81. Kendal Dump Ash in tables 9 and 10 varied from 0.86 to 2.81. All three are well below the required standard of not greater than 5%. (SANS 1491-2, 2005). LOI will not limit strength of hydrated Fly Ash as long as the Fly Ash contains sufficient lime to react with the three main ingredients of Fly Ash namely: Ferric Oxide, Aluminium Oxide and Silica (FAS) (Conn, 1997). Class F Fly Ash has very low free lime content therefore, it will be critical that the LOI is low for the purpose of strength gain over time.

SO_3 must be low to prevent formation of calcium sulphite that will cause the formation of ettringite. Ettringite increases volume, expansion and cracks can occur (Conn, 1997; Fulton, 2009). Free lime will form free $Ca(OH_2)$ when mixed with water and when in contact with carbon dioxide (CO_2) will form carbonates as shown in the formulae:

$Ca(OH_2) + CO_2 \rightarrow CaCO_3 + H_2O$

This reaction will cause that the stabilization process will no longer continue and the preservation of the cementing compounds will cease as the stabilized materials are reverted to un-cemented, granular materials. Free Lime is one of the key components that influence the strength of hydrated ashes. The main components of Fly Ash are amount of free lime in combination with FAS that influence the strength of hydrated ashes (Conn, 1997). The free lime, once hydrated to CaO, would undergo pozzolanic reactions with FAS to form complex hydrates as shown in the following formulae:

$SiO_2 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2._2H_2O_2$
$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO.Al_2O_3._2H_2O$
$SiO_2 + Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.Al_2O_3._2H_2O$
$Fe_2O_3 + Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow CaO.Al_2O_3.Fe_2O_3._2H_2O$

Physical Characteristics

The fineness for DURAPOZZ is within specified limits of less than 12.5% as shown in tables 1 and 4, which the results varied from 9.7% to 11.1%. POZZFILL and Kendal Dump Ash do not make the required specifications as the results varied from 32% to 35.2% in tables 5, 8, for POZZFILL and varied from 27.9% to 48.3% in table 10 for Kendal Dump Ash. The gradation of Fly Ash is an important factor as a coarse gradation could lead to less reactive ash and could contain higher carbon contents (FA FACTS, Ancuta, 2010; Conn, 1997). The Fly Ash particles range from 3.350mm to 0,002mm for Kendal ash as seen in figure 1 and 0.300mm to 0,002mm for both Durapozz and Pozzfill as seen in figure 1. It has been noted in a recent study that at least 40% of the sample should pass the 10 micron sieve (1000 microns = 1mm) as these are the particles that contribute to the strength regardless of the type of the Fly Ash (Mehta,1998). Samples above the 0,300mm sieve are considered inert, as they do not participate in pozzolanic reactions. Particles between the 0.010mm sieve and the 0,300mm sieve are the ones that slowly react. Durapozz and Pozzfill Fly Ash have most of the particle sizes between 0,020mm sieve and 0,300mm sieve therefore these will react slowly over time.

The Kendal Dump Fly Ash has a variation in particle sizes reading from 81 percent passing the 0,300mm sieve to 21percent passing the 0,020mm sieve. These will react slowly as previously stated above but the material above the 0,300mm sieve will be inert material and will basically behave like sand, which will only contribute to the granular modulus of the material (Mehta, 1998). As stated, particles passing the 10 micron sieve is very critical, as these are the more reactive particles. Durapozz Fly Ash has the highest of passing the 20 micron sieve of 54 percent followed by Pozzfill Fly Ash with 37 percent passing the 20 micron sieve and then Kendal Dump Fly Ash with 21 percent. The particles passing the 0.005mm sieve has shown a reverse as previously stated as the Kendal Dump Fly Ash has more particles passing the 0.005mm sieve than compared to the Durapozz Fly Ash and Pozzfill Fly Ash.

It was also stated that at least 40 percent should pass the 10 micron sieve for more reactive material but this is not the case with Kendal, Durapozz or Pozzfill as seen in figure 1. It is also one of the reasons why Class F Fly Ash requires a cementing agent to form pozzolanic reactions for early strength gain, after the initial strength gain, the three Fly Ashes in this study have enough pozzolanic material to continue with the slow reactions, which will occur continuously over time. Both Durapozz Fly Ash and Pozzfill Fly Ash are fine silty Fly Ashes, which is common of Fly Ash and can be used to improve gradings of coarse granular materials. Kendal is coarse graded but can be of value to weaker material to improve grading thus increasing the strength values of the material.

Tables 4, 8 and 10 show the sampling of Fly Ash over a 7 day period where gradation was conducted on each sample. It is typical values taken at various loads dispatched. The color of each of the Fly Ash specimens varied from pale grey for DURAPOZZ, Light grey for POZZFILL to dark Grey for Kendal Dump Ash. The color depends on its' chemical and mineral constituents. Fly Ash is very consistent for each power plant and coal resources. The tan color is associated with high lime content and dark grey is associated with unburned carbon content (FA FACTS, 2003).

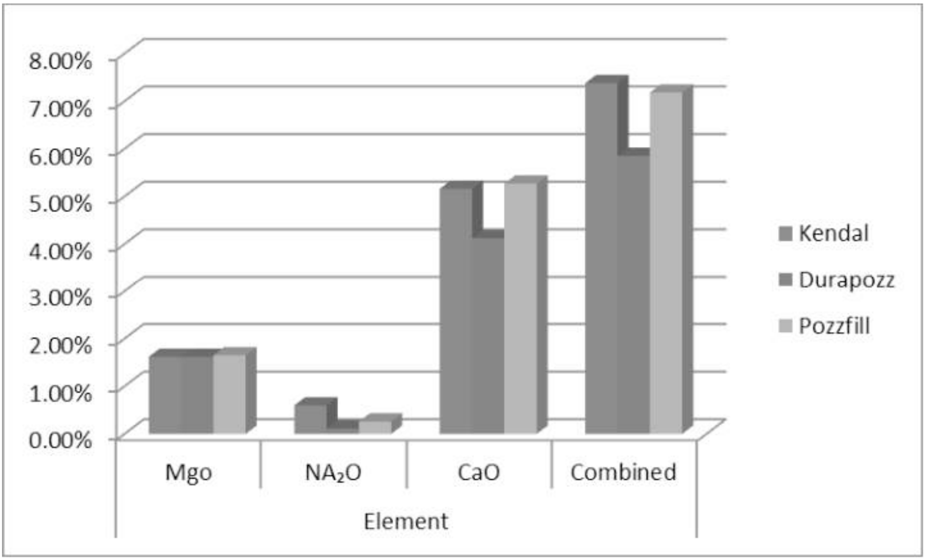

Figure 2 Strength Gain Elements

One should also take into account the values of Sodium, Magnesium and Calcium as the combination of these three will also contribute to strength gain. As shown in figure 2, the values shows that Kendal has shown a much higher value, which will give the advantage to Kendal Dump Fly Ash for better strengths gain in the early stages of stabilization.

6. CONCLUSIONS

Fly Ash is an abundant mineral found in South Africa, which is highly variable, both physically and chemically. A complete characterization was made to develop a complete comparative data and possibly set up combined standards for characterization of Fly Ash in South Africa. The set of standards chosen to evaluate the Fly Ash to obtain suitability for various applications that Fly Ash can be utilized in the construction industry was obtained from Fly Ash utilization in Concrete and Soil Stabilization standards. The tests conducted and results obtained, determined several points:

- Classify Fly Ash
- Evaluate cementing potential
- Determine the LOI
- Determine Sulphur content
- Determine Free Lime
- Analyze other chemical components, which contribute to strength characteristics.

Fly Ash in South Africa is classified as Class F therefore all Fly Ash that will be used in construction industry need a cementing agent to sure proper reactions to take place and the continuation of the reaction over a period of time. The following main results were identified for evaluation of Class F Fly Ash for construction purposes:

- The cementing potential is low therefore, it is critical to use a cementing agent in the form of Lime/Cement to produce immediate reactions.
- SiO2 values are high for all three Fly Ashes, which will form stable cementitious compounds with calcium hydroxide, which will allow pozzolanic reactions for a long period of time.
- LOI will not limit strength as long as there is enough lime to for continuous reaction but in the case of Class F Fly Ash, there is no sufficient lime therefore it is critical to keep the LOI as low as possible
- Sulphur must be kept low to contain any formation of calcium sulphate to form ettringite
- Limit the amount of free lime as this will form Calcium Hydroxide when mixed with water and when in contact with Carbon Dioxide, will form carbonates
- The gradation of Fly Ash contributes to strength. 75% of the Fly Ash must pass the 45 micron sieve for proper reactions to take place.

It is critical that the fineness of Fly Ash be within limits stated by ASTM, stabilization standards will greatly depend on Fly Ash fineness and its particle size distribution.

Although SANS 1491-2 (2005) states that the Fly Ash % retained on the 45μm sieve must not exceed 12.5%, it is however specified in AASHTO M295 (ASTM C618) that maximum allowable to be retained on the 44μm sieve is not to exceed 34%. It can then be stated that with SANS 1491-2 only DURAPOZZ can utilized if the required specification is enforced but with AASHTO M295, all three Fly Ashes can be utilized for design and construction purposes.

To use and design with Fly Ash, it is imperative that the supply of Fly Ash be uniform in order to supply a consistent product. Both DURAPOZZ and POZZFILL are consistent with gradation and LOI requirements due to that both DURAPOZZ and POZZFILL are already processed but the Dump Ash varies with gradation requirement due to that it is sampled directly from the disposal landfill sites. This can be overcame by installation of mechanical sieve operations that can sieve out the fly ash to a uniform standard so that the percentage retained on the specified sieve is obtained throughout the construction process.

The three Fly Ashes in the this study needs an cementing agent as per information provided therefore it is recommended that the Fly Ash conforms to the standards set out and discussed in this document to make sure that proper reaction will take place and that the reaction continues over a period of time.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

ASTM C618,994, "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete," American Society for Testing and Materials, Annual Book of ASTM Standards, Volume 04.02, West Conshohocken, Pennsylvania.

British Standards (BS) 3892-2:1997, "Specification for pulverized fuel ash with Portland cement".

Cement & Concrete Institute, 2009, cementitious materials for concrete standards, selection and properties.

Committee of Land Transport Officials (COLTO), 1998 Edition.

Conn, R.E, and K. Sellakumar, 1999;" Utilization of CFB Fly Ash for construction applications" Paper No. FBC99-0144, Proceedings of the 15th annual International Conference on Fluidized Bed Combustion.

Fly Ash Facts for Highway Engineers, 2003, Technical Report Document, Report No: FHWA-IF-03-019.

Fulton's Concrete Technology, Ninth Edition, 2009.

Guyer, P.E., R.A, Fellow ASCE, Fellow AEI, 2011; ”Introduction to Soil Stabilization in Pavements” Course No: C03-028.

Mehta,P.K.,1998, ”Role of Fly Ash in Sustainable Development – Concrete, Fly Ash, and the Environment – Proceedings” Forum held – Sponsored by EHDD Architecture and Pacific Energy Center.

Ojo F, 2010, “Chemical interactions and mobility of species in fly ash-brine co-disposal systems” Thesis published for Doctoral in Chemistry, Department of Chemistry, University of Western Cape.

Rotaru, Antcuta, Vasile Boboc, 2010;”A Material Used in Substructure and Road Works: Physical Characteristics of Pozzolona Fly Ash from Thermal Power Plant of Iasi, Romania” Issue 6, Volume 6.

South Africa National Standards (SANS) 1491-2, 2005, “Portland cement extenders Part 2: Fly Ash”.

South Africa National Standards (SANS) 50197-1, 2000, “Cement Part 1: Composition, specifications and conformity criteria for common cements”.

South Africa National Standards (SANS) 50197-2, 2000, “Cement Part 2: Conformity evaluation”.

Standard Methods of Testing Road Construction Materials, TMH1, 1986.