

Characterization of the surface and physical properties of South African coal fly ash modified by sodium lauryl sulphate (SLS) for applications in PVC composites

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ABSTRACT

The application of coal fly ash as mineral filler in polymers is hampered by the aggregation of the ash particles and a lack of interaction between the ash and polymer. Therefore surface treatment is usually performed on mineral fillers to enhance workability and compatibility between the polymer and filler. In this study, a commercially available South African coal fly ash sample was surface modified under a variety of conditions with an anionic surfactant, sodium lauryl sulphate (SLS), with the aim to alter the surface properties of the ash. The properties of the modified products were compared to those of the untreated samples by means of scanning electron microscopy (SEM), transmission electron microscopy (TEM), thermogravimetric analysis (TGA-IR), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) X-ray fluorescence spectroscopy (XRF). A small shift of the S-O stretch vibration in FTIR spectra of SLS treated fly ash is indicative of interaction between fly ash and SLS. Although the overall chemical composition of the SLS modified coal fly ash sample was not altered extensively, significant changes could be observed in its physical properties. Contact angle measurements indicated that the hydrophilic surface of untreated fly ash was rendered hydrophobic after SLS treatment. SEM and TEM results showed agglomerates on the surface of most of the fly ash spheres. Feasibility tests of using fly ash samples as filler in PVC indicated that SLS treated fly ash can successfully replace CaCO_3 as filler in PVC under conditions of low filler loadings.

KEYWORDS: coal fly ash (FA), surfactant, sodium lauryl sulphate, SLS, surface modification, PVC

1. Introduction

A very small percentage of coal fly ash produced worldwide is currently being exploited and with the growing concern about pollution and increasing landfill costs, there has been global interest to increase the utilization of coal fly ash. Benefits for doing so include a reduction in the usage of non-renewable natural resources and the substitution of materials that may be energy intensive to manufacture. One possible use of coal fly ash is as filler in polymers and rubber.

Fillers are generally used in polymers and rubber to reduce their production costs and to improve certain physical characteristics. The physical properties of coal fly ash make it a suitable filler for polymers. In particular, the sphericity of coal fly ash particles facilitates dispersity and fluidity within polymeric materials, while the reduced density and cost of fly ash adds to the list of advantages when compared to conventional fillers. However, the application of coal fly ash in these fields is not common yet. One of the principle problems is that there is no binding between the polymer and fly ash, with the consequence that the quality of the product is unsatisfactory. Another concern is the agglomeration between fly ash particles, which has an adverse effect upon its workability as filler. If the surface properties of fly ash can be modified in such a way that these problems are conquered, a new market for the utilization of fly ash can materialize.

Research in the field of utilizing fly ash as filler in different polymeric materials is growing exponentially [1-11]. Surface treatment is a principal method applied to change the wetting behaviour of mineral or inorganic fillers. Surfactants are generally used as surface modifiers to increase the hydrophobicity of the surface of hydrophilic inorganic fillers, which consequently increases compatibility between the polar inorganic and non-polar organic matrices. Nath et al [7, 8] studied the effect of surfactant sodium lauryl sulphate (SLS) modified fly ash on the properties of composite films fabricated with polyvinyl alcohol (PVA). Their results showed an enhancement in the physical properties (increased tensile strength) of the polymer, which they attributed to the elimination of particle-particle interaction, and a better distribution of fly ash within the polymer. The composition and morphology of the fly ash used in the study performed by Nath [7, 8] differ from

that of South African fly ash, and the method would not necessarily be successful when applied to South African fly ash.

In a preceding paper the bulk and surface properties of the classified South African FA sample used in this study was characterized using a variety of techniques [12]. In this study we develop a method for modifying the surface properties of this sample using sodium lauryl sulphate (SLS) and report the changes in properties (including surface coverage) as well as feasibility tests to determine whether SLS modified fly ash can be used as replacement of the conventionally used CaCO_3 as filler in PVC.

2. Material and Methods

2.1. Materials

The coal fly ash (FA) utilized in this study was obtained from the Ash Resources Pty Ltd ash beneficiation site at Eskom's Lethabo Thermal Power station. The fly ash is classified on site and is specified to have a mean particle size between 3.9 and 5.0 μm with more than 90% of its particles with diameters less than 11 μm . After classification it is marketed as a very fine, spherical, pozzolanic and highly reactive alumino-silicate with low carbon content. Sodium Lauryl Sulphate (SLS) with a purity of 98% was obtained from Merck and was used as received

2.2. Coal Fly Ash modification

20 g of a dry FA sample was either mixed with 200 ml distilled water or the relevant SLS solution. The effect of varying the surfactant concentration (0.1%, 0.5% and 2.0% wt), temperature of treatment (50 °C and 80 °C) as well as treatment time (6, 18 and 66 hours) was studied. The FA aqueous suspensions were treated in a shaking waterbath at the relevant temperature while shaking continuously at 130 revolutions per minute.

For the reflux experiments, a reflux system consisting of a heating mantle, round bottom flask and condenser was assembled. The mixtures were refluxed for 6 hours using water and SLS solutions with concentrations of 0.5%, 2.0%, and 4.0% by weight.

After the respective treatments, the samples were washed with distilled water numerous times under vacuum filtration, and subsequently dried for 2 days at 50 °C in a laboratory oven. A new surfactant solution was prepared every day, in order to minimise chances of decomposition of SLS that may occur during storage [13].

2.3. Chemical analysis by X-ray fluorescence spectroscopy (XRF)

XRF was used to determine the bulk chemical concentrations of major elements in the untreated FA sample. No milling was required prior to the analysis. The analysis was performed on an ARL9400XP+ XRF spectrometer (Thermo ARL, Switzerland). The loss on ignition (LOI) was determined by roasting the sample at 1000 °C for at least 3 hours until a constant weight was obtained. A glass disk was prepared by fusing a mixture of 1 g of the FA sample with 6 g of $\text{Li}_2\text{B}_4\text{O}_7$ at 1000 °C.

2.4. X-ray diffraction (XRD) analysis

The mineralogical composition of the FA sample was obtained by XRD. The XRD patterns were collected from 5° to 90° on a PANalyticalX'Pert Pro powder diffractometer with X'Celerator detector and variable divergence and fixed receiving slits with Fe filtered $\text{Co-K}\alpha$ radiation. The phases were identified using X'PertHighscore plus software. The relative phase amounts were estimated using the Rietveld method (Autoquan Program). Twenty percent silicon (Aldrich 99% pure) was also added to each sample for the determination of amorphous content. The samples were then micronized in a McCrone micronizing mill, and prepared for XRD analysis using a back loading preparation method.

2.5. Scanning electron microscopy (SEM)

The FA powder was mounted on a double-sided carbon tape by dipping carbon stubs into the samples. Excess material was removed by gentle blowing with compressed nitrogen. The samples

were then coated with either gold or carbon using a Sputter-coater (Emitech K550X, Ashford, England).

The gold coated samples were analysed on a JEOL JSM 840 Scanning Electron Microscope (SEM), operated at 5kV. Images were collected with the aid of a flame-grabber (Orion Version 6). To study the carbon coated samples, a Zeiss Ultra SS (Germany) field emission scanning electron microscope (FESEM), operated at an acceleration voltage of 1 kV, was used under high-vacuum conditions.

2.6. Transmission electron microscopy (TEM)

A JEOL JEM 2100F TEM was used to study the topography of the FA. The samples were dispersed in 100% ethanol with the aid of sonication. A drop of the diluted suspension was poured onto a copper grid which was then placed into the sample injection holder for analysis.

2.7. Infrared spectroscopy (FTIR) studies

Mid-infrared spectra were recorded with a Brüker 70v Fourier transform infrared (FTIR) spectrometer, by placing the finely grounded samples in a diamond ATR (attenuated total reflection) cell. The resolution was 2 cm^{-1} and 32 scans were signal-averaged in each interferogram.

2.8. TGA-IR analyses

TGA-IR analyses were performed on a Perkin Elmer Spectrum 100 FT-IR spectrometer coupled to a Perkin Elmer TGA 4000 Thermogravimetric Analyzer. Approximately 20g was placed on an alumina pan and heated in air at 10 $^{\circ}\text{C}/\text{min}$.

2.9. Contact angle

Contact angle measurements were performed on an OCA-20 Contact Angle-meter (Data Physics Instruments), using the sessile drop method with water as wetting liquid. To perform these measurements, a small drop of water is deposited on the surface of a FA powder bed which was

fixed to a microscope slide by double-sided tape. A picture of the profile of the drop is taken about 1 second after contact with the powder surface. The reported result is the average of three measurements.

2.10. Preparation of FA-PVC composites

In order to investigate the effect of surface modification on a PVC composite, the untreated FA sample, 4.0% SLS reflux FA sample and a 2.0% stearic acid coated CaCO₃ filler was used. Flexible PVC composite sheets were made using a Ca/Zn stearate stabiliser and dioctyl phthalate plasticiser. Three different ratios of filler to resin were used, as indicated in Table 1. For comparison purposes, a 2.0% stearic acid coated CaCO₃ filler was included in at a filler to resin ratio of 30 phr, keeping the amounts of stabilizer and plasticiser the same as for the 30 phr FA filled PVC samples.

Table 1: Formulation of the PVC composites

Material	Parts per hundred resin (phr)
PVC S68	100
Filler (Fly ash or CaCO ₃)	30, 40 or 70
Stabiliser (Ca/Zn stearate)	3
Plasticiser (Dioctyl phthalate)	40

The dry samples, which include the PVC resin, the filler, and the stabiliser, were mixed together in a high speed mixer for 3 minutes before the liquid plasticiser was added to the mix. After adding the plasticiser, the contents were mixed together in the mixer for a further 5 minutes. The sample was collected and milled on a two roll bridge mill at 168 °C.

2.11. Tensile tests

Tensile testing was performed at a constant speed of 50 mm/min with a gauge distance of 50 mm according to ISO 527 for tensile strength and elongation analysis on flexible sheets; along the direction of milling as well as the transverse direction. The samples were cut with a die cutter, and the data reported is the average of 5 specimens taken from each direction. The samples were

conditioned in the laboratory for 36 hours at 23 °C and a humidity of 43% before performing tensile tests.

2.12. Relative density

The relative densities of the PVC composites were measured at 25 °C and a pressure of 1 atm using a Micromeritics AccuPyc II 1340 Gas Pycnometer.

3. Results and discussion

3.1. Chemical and mineralogical characterisation

The chemical composition as determined by XRF analysis (Table 2) is typical of a Class F coal fly ash, and the low loss on ignition value indicates that the ash contains a very low percentage moisture, carbonates and hydroxides. This result was confirmed by TGA analyses (Section 3.5, Figure 7).

Table 2: Elemental bulk composition of the fly ash sample, as determined by XRF (major elements)

Composition	Weight %
SiO ₂	49.30
TiO ₂	2.01
Al ₂ O ₃	34.00
Fe ₂ O ₃	5.78
MnO	0.05
MgO	0.99
CaO	5.06
Na ₂ O	<0.01
K ₂ O	0.87
SO ₃	0.24
P ₂ O ₅	0.59
Cr ₂ O ₃	0.07
NiO	0.05
V ₂ O ₅	0.04
ZrO ₂	0.08
Loss on Ignition	0.52
Total	99.63

XRD analysis (Figure 1) determined that the FA sample was predominantly composed of an amorphous alumina silica glass phase (62.1%), and that the two main crystalline phases were mullite (31.8%) and quartz (6.1%). No significant difference was observed between the quantitative

XRD analysis of the untreated FA and SLS modified FA samples as expected as interaction between FA and SLS is purely a surface effect.

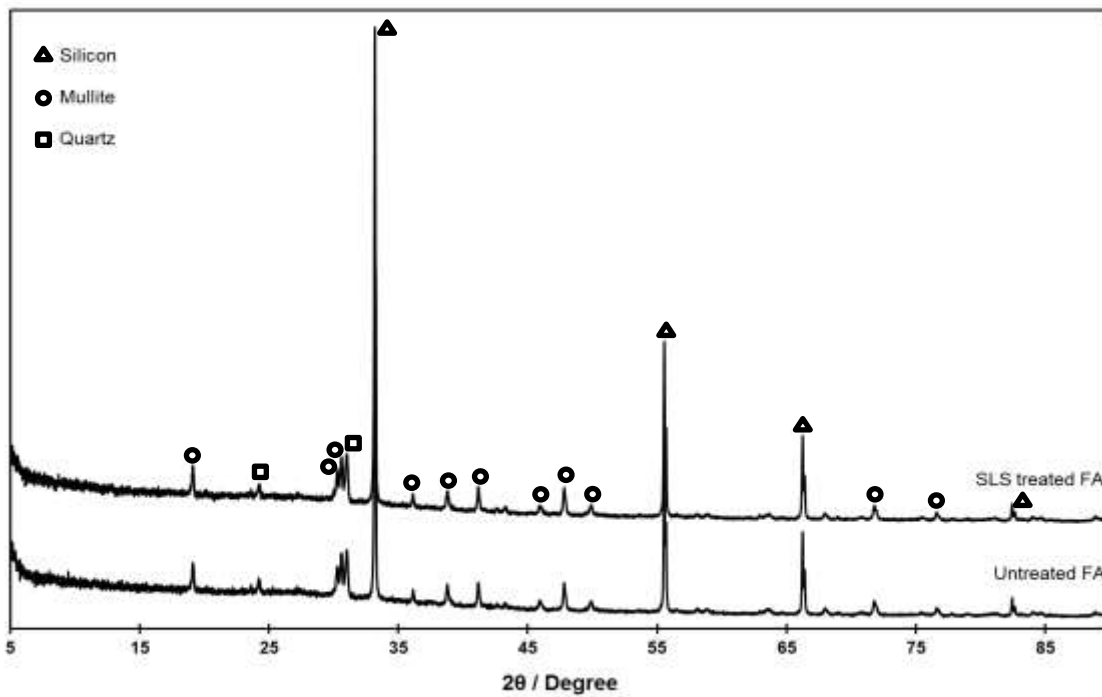


Figure 1: XRD analysis

3.2. Morphological characterisation

The results obtained from SEM measurements for the untreated FA and the FA samples treated with varying concentrations of SLS for 6 hours at 80°C in the shaking water bath are shown in Figure 2. It is clear that the samples have good sphericity and a decrease in the formation of agglomerates (Figure 2) occur as the concentration of SLS increases; indicating that SLS

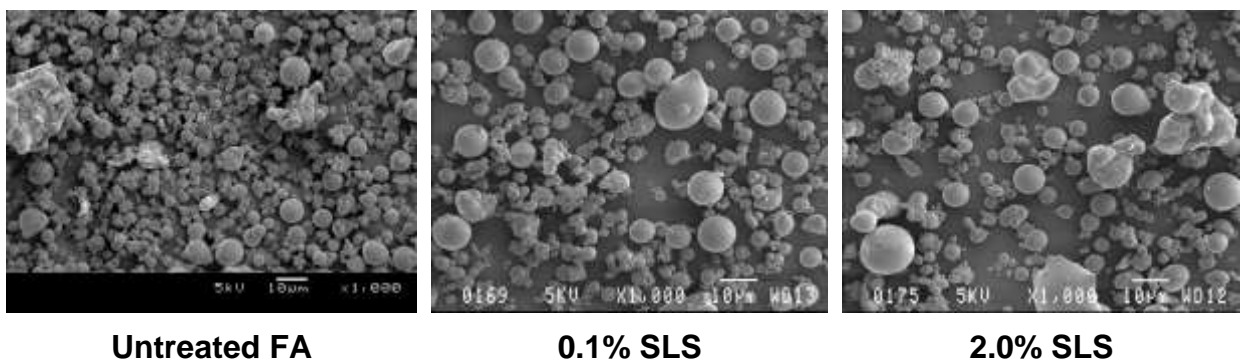


Figure 2: Results obtained from SEM measurements for the untreated FA and the FA samples treated with varying concentrations of SLS for 6 hours at 80 °C in the shaking waterbath

treatment of FA samples improves the separation between particles. It should be noted that water treated samples also showed a slight reduction in agglomeration which could be due to mechanical action, as samples were subjected to vigorous shaking during treatment. Considering temperature conditions, the extent of particle separation was greater for the samples treated at 80 °C than at 50 °C, and therefore only the results obtained for the 80 °C treatments are shown here.

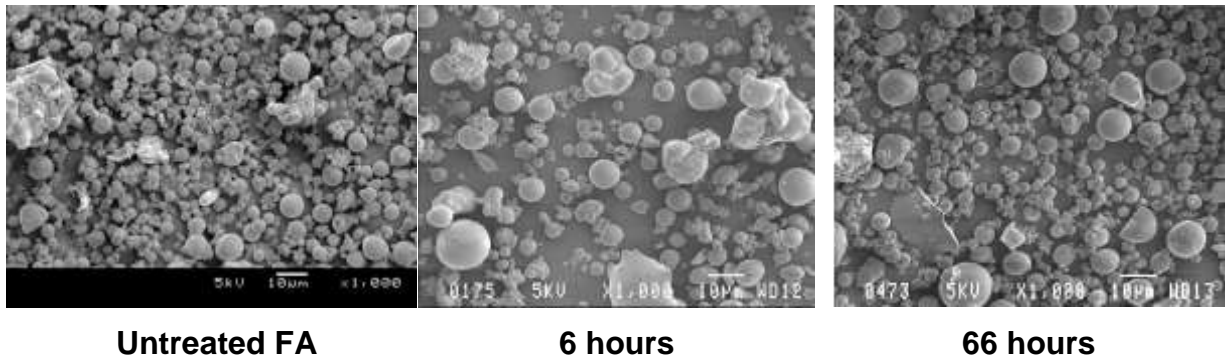


Figure 3: Effect of increasing the treatment time (80 °C)

The effect of increasing the treatment time (80°C) is shown in Figure 3 and it is clear that the SLS-FA sample treated for 6 hours shows a higher degree of particle separation in comparison to the 66 hours treated sample. One explanation may be that the presence of silanol groups on the surface of the fly ash particles causes strong interactions between particles leading to agglomeration as reported by Wolff [14] for a filler in a rubber matrix. On the other hand it has been reported by Sugàr et al [13], that SLS solutions will degrade with time, and that fresh solutions need to be prepared on the day of use. It is possible that the SLS solutions decayed during treatment leading to a decrease in separation of agglomerates. Further investigation is necessary for clarification

A summary of the most promising results, obtained from FESEM analysis, is shown in Figure 4. The occurrence of agglomerates on the surface of the SLS-modified FA samples is clear. The agglomerates on the surface of the FA sample treated in 4.0% SLS under reflux conditions seem to be more evenly distributed compared to those on the surface of the FA sample treated in a 2.0% SLS solution at 80 °C.

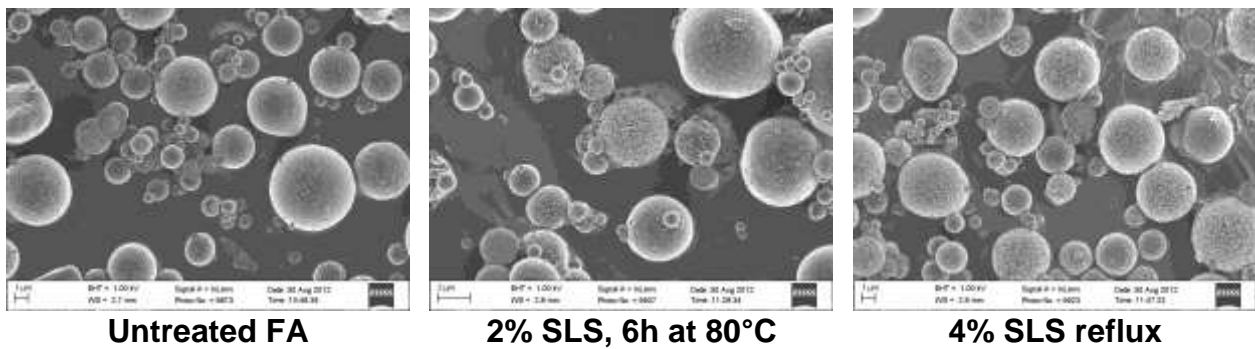
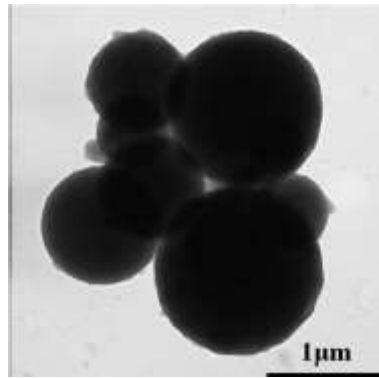


Figure 4: Summary of the most promising results, obtained from FESEM analysis

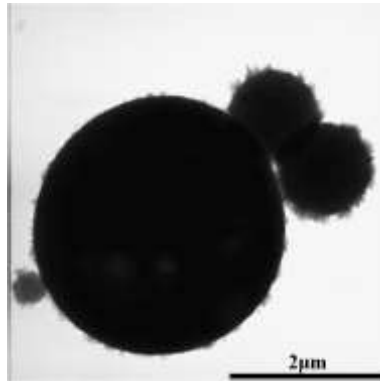
Particle coating was observed for all the SLS reflux treated samples with a higher degree of surfactant coverage on the surface of the 2.0% and 4.0% SLS modified FA, whereas significant numbers of FA particles of these treated samples were found to be coated. The FESEM images of the SLS refluxed FA samples show an even distribution of the coating of particles as well as the density of the coating, indicating that most of the FA particles were coated with the surfactant.

3.3. Topographic characterisation

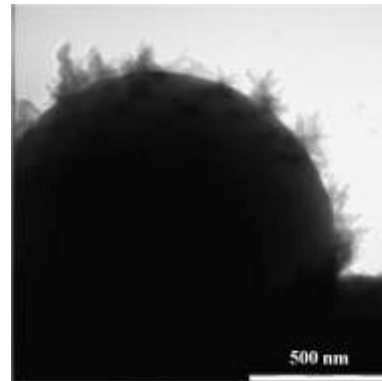
Results obtained from Transmission Electron Microscopy (TEM) measurements are summarized in Figure 5. Most of the TEM images show agglomerates on the surface of the fly ash spheres. However, there is a distinct difference between the morphology of these agglomerates on the untreated and SLS modified FA. The agglomerates on the untreated FA spheres are considerably less than those on the SLS modified FA. Not all SLS modified FA particles were covered with agglomerates to the same degree. This is depicted for the FA sample treated in 2.0% SLS at 80°C in Figure 5 (b). Under the same treatment conditions, some FA spheres had a low degree of coverage, while others were covered extensively. Also, the needle-like shape of the agglomerates on the SLS modified FA was different from that of the agglomerates observed on the untreated (Figure 5(a)) and water treated FA surfaces (not shown), which were more rounded in shape. Both Chen [15] and Hower [16] described the occurrence of carbonaceous agglomerates on different types of untreated FA particles. The morphology of the agglomerates described by these authors was distinctly different from that observed in the SLS modified FA in this study.



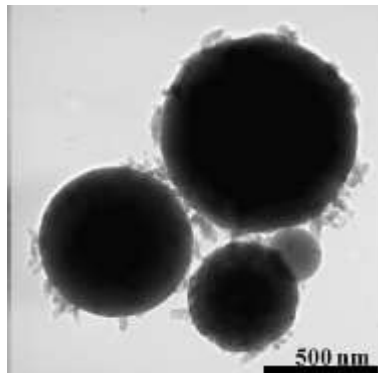
(a)



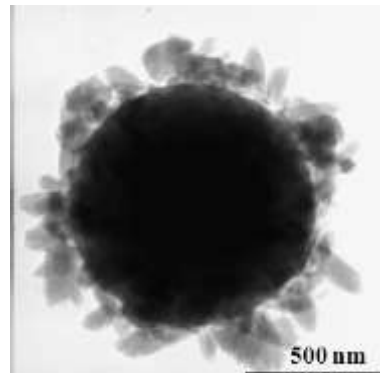
(b)



(c)



(d)



(e)

Figure 5: Results obtained from transmission electron microscopy (TEM) measurements of (a) untreated FA; and FA treated in (b) 2.0% SLS at 80 °C, (c) higher magnification of the surface of the fly ash sphere in (b), (d) 2.0% SLS under reflux conditions, (e) 4.0% SLS under reflux conditions

The morphology of the coating on reflux modified FA samples (Figure 5 (d) and (e)) was seen to be different from those seen on the 2.0% SLS modified sample at 80 °C (Figure 5 (b) and (c)). The SLS agglomerates on the reflux modified FA samples are tighter and thicker, and extensive coverage of some FA particles was observed for the 4.0% SLS refluxed sample.

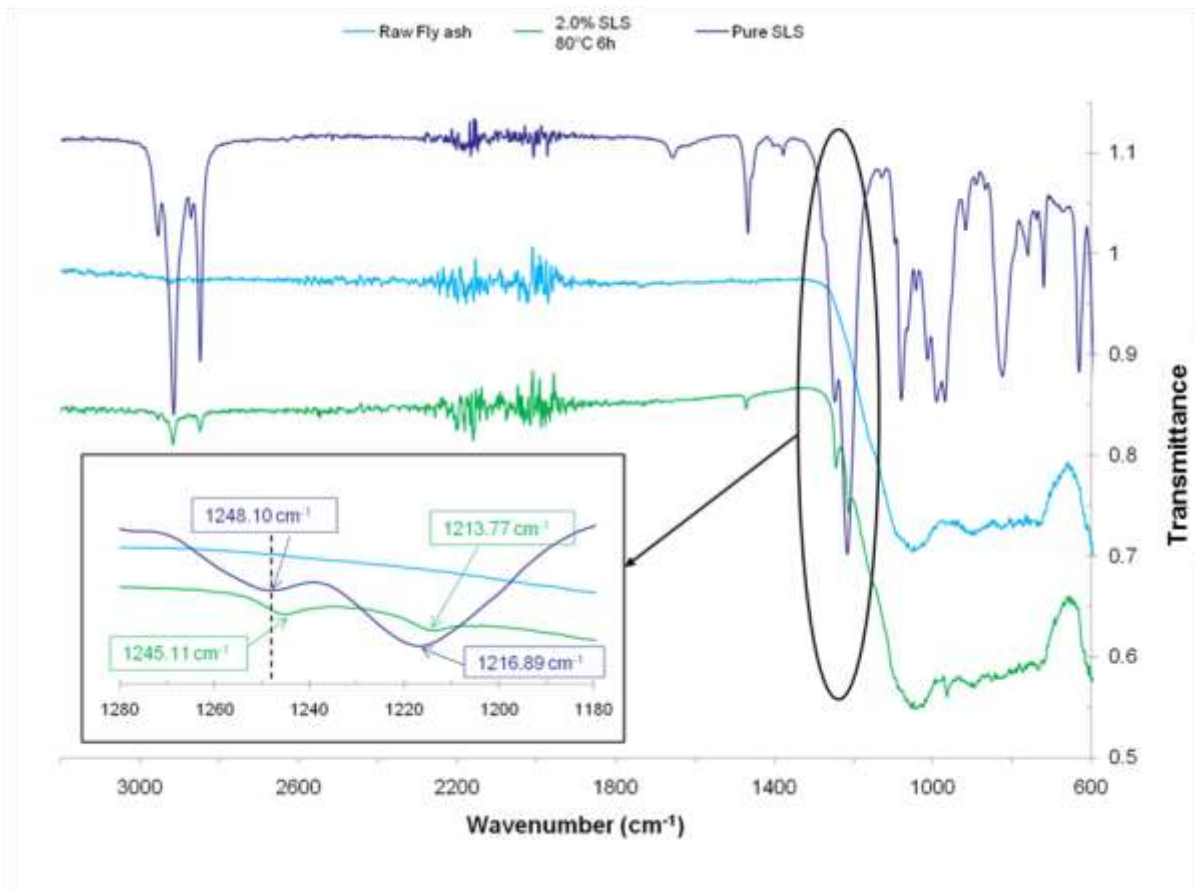


Figure 6: Mid-infrared spectrum of the sample treated with 2.0% SLS at 80 °C for 6 h

3.4. Spectroscopic analysis

The mid-infrared spectrum of the sample treated with 2.0% SLS at 80°C for 6h is shown in Figure 6. For comparative purposes the spectrum of pure SLS and the untreated FA is included in the figure. The spectra of the SLS modified and untreated flyash are identical except for a few small sharp peaks appearing at the exact positions of the SLS bands. A closer look (insert) shows that the peaks at 1248 and 1216 cm^{-1} , assigned to S-O stretch vibrations, have shifted slightly towards lower wavenumbers indicating a weakening in S-O bond strength. This is an indication of interaction between SLS and the fly ash surface and as the shift is quite small it could be attributed to electrostatic interaction. The peaks in the C-H stretch region (2840-3000 cm^{-1}) do not display a shift; therefore it points to interaction through the sulphate anion implying that the hydrocarbon chain is aligned outwards from the fly ash kernel. This would explain the hydrophobic behaviour observed in the wettability experiments (section 3.6) and is in line with the shape of the protrusions observed on the surface of the treated fly ash spheres in the TEM photographs. It should be noted that this was not observed in all of the spectra recorded for this sample which suggests that the

particles are not evenly coated with SLS, an observation which is in accordance with the results obtained from the TEM measurements. In some of the spectra recorded on other modified samples the same peaks were observed, but with lower intensities.

3.5. Thermal stability

The results obtained from TGA-IR analyses of the untreated FA, pure SLS and SLS modified FA are presented in Figures 7 - 9. SLS decomposes in the region 200 - 300 °C, and therefore TGA-IR measurements were performed only up to 400 °C. FT-IR spectra of the decomposition products were acquired at regular time intervals throughout the thermal measurement performed in the TGA.

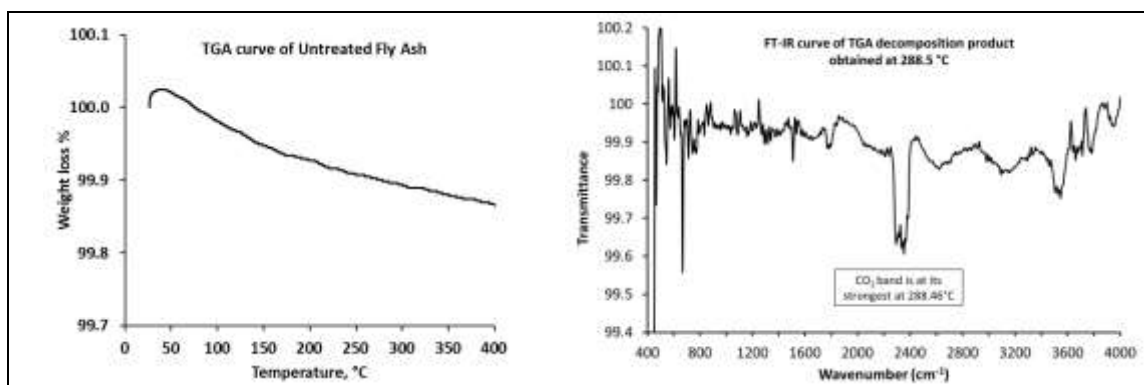


Figure 7: Results obtained from TGA-FTIR analyses of untreated FA

The very small weight loss percentage (0.1%) observed for the untreated FA sample (Figure 7) over the temperature range of interest, can be ascribed to loss of moisture and oxidation of residual coal, present in low percentages in the fly ash. This was confirmed by the occurrence of the CO₂ band in the FT-IR of the decomposition gas, taken at 288 °C. However, most of the residual coal trapped in the glass matrix will oxidize at temperatures exceeding 400 °C and this peak probably originates from carbon close to the surface of the glass spheres. No other decomposition products were observed for this sample, within the detection limits of the instrument. The low weight loss observed from the TGA-FTIR is in agreement with the low loss of ignition that was observed on the XRF analysis.

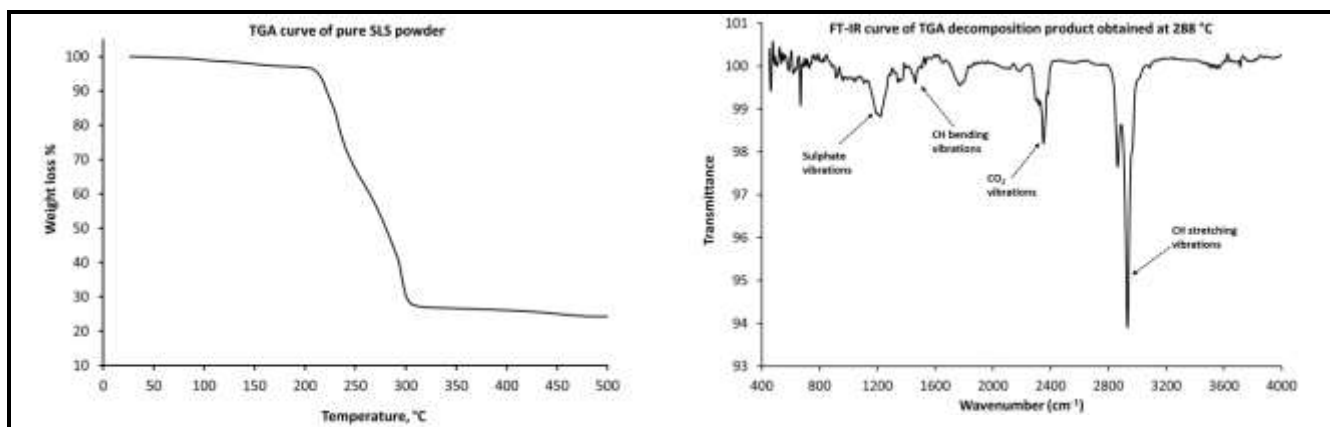


Figure 8: TGA-FTIR analysis of pure SLS

The TGA curve of pure SLS (Figure 8) shows a small weight loss corresponding to the loss of water between 100 and 200 °C. Between 200 and 300 °C, a significant weight loss occurred with a corresponding evolution of CO₂, sulphates and hydrocarbons from the sample. The FTIR spectrum of the gaseous decomposition product, taken at 288 °C is shown in Figure 8. Characteristic peaks of the aliphatic chain of SLS are observed at approximately 1438 and 2930 cm⁻¹ for bending and stretching CH₂ bands respectively. The CO₂ band was prominent at 2346 cm⁻¹ with that of the inorganic sulphate noted at approximately 1165 cm⁻¹. The occurrence of CO₂ as decomposition product of pure SLS is possibly due to oxidation of the alkyl chain. These measurements were performed in an air atmosphere. Sreedhar [17] has also reported the occurrence of CO₂ upon thermal decomposition of SLS-doped polyaniline between 260 – 600 °C, as studied by TGA coupled with mass spectrometry.

Thermal analysis of SLS modified FA portrayed a different picture, as can be seen in Figure 9. The results obtained for the 4.0% SLS refluxed FA was similar to the data reported in Figure 9. A significant weight loss was observed over the temperature range 230 - 250 °C, and two decomposition products were observed in the FT-IR data. Firstly, C-H stretching vibrations were observed and were found to be strongest at a corresponding TGA temperature of 236 °C, which is consistent with the 0.4% weight loss observed at this temperature. This decomposition product can be ascribed to the presence of hydrocarbons originating from the SLS in the modified FA sample. Secondly, the vibrational bands of CO₂ were also observed over a wide temperature range, and were found to be strongest at 319 °C. This can be ascribed to the onset of oxidation of residual

coal within the fly ash as well as the decomposition product of the SLS on the surface of the fly ash particles.

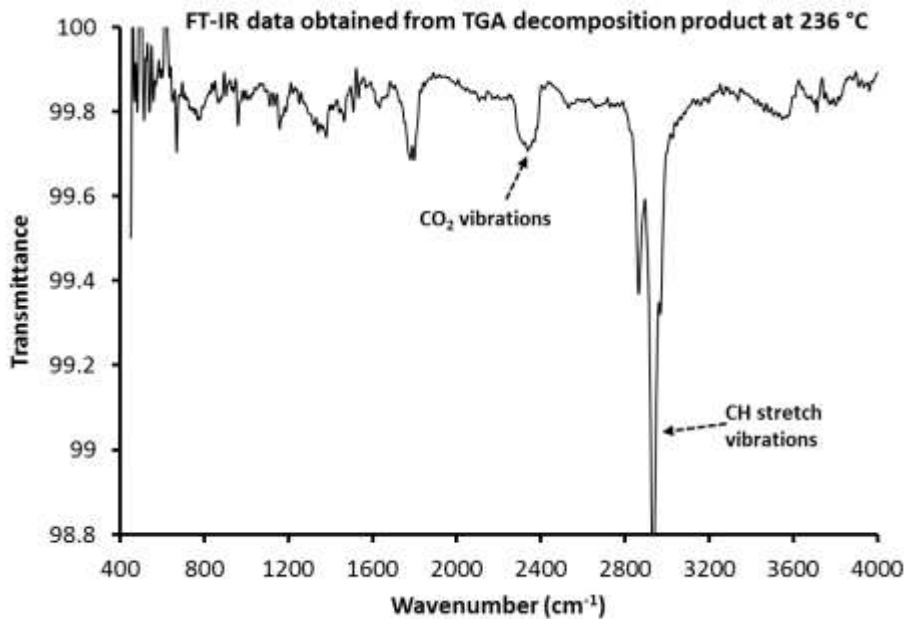


Figure 9: Thermal analysis of SLS-modified FA

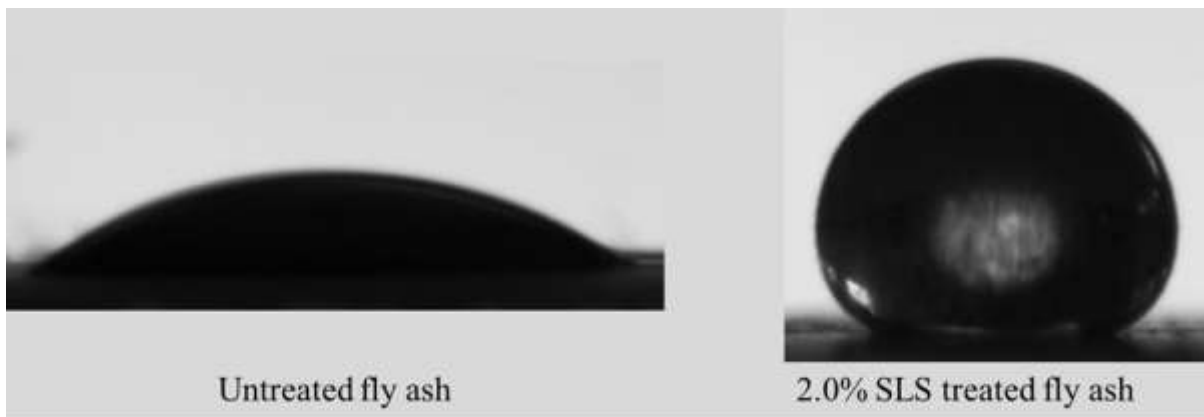


Figure 10: Example of the results obtained from wettability tests

3.6. Wettability

An example of the results obtained from wettability tests is shown in Figure 10. The contact angles of untreated and SLS modified FA samples were measured using water as wetting liquid. Untreated FA was found to be hydrophilic with an initial contact angle of approximately $39 \pm 1^\circ$. The results obtained for the FA sample treated in 2.0% SLS for 6 hours at 80 °C and the sample refluxed in 4.0% SLS were similar. The 2.0% SLS modified FA has shown an initial contact angle of $137 \pm 1^\circ$ while that of the 4.0% refluxed sample was $140 \pm 3^\circ$, indicating a very hydrophobic surface.

3.7. Mechanical properties of the FA-PVC composites

The 4.0% reflux treated FA sample was tested for use as filler in a PVC composite and the results were compared to that of untreated FA and a 2.0% stearic acid coated CaCO₃, a commonly used filler in PVC. The relative densities of the different formulations are reported in Table 3. The values were found to range between 1.37 to 1.47 g/cm³ indicating values typical of a rigid PVC [18]. Comparing the fillers at 30 phr, the FA filled PVC composite was slightly lighter than the CaCO₃ filled composite. Similar relative densities were obtained for the 30 phr CaCO₃ composite and the 40 phr FA composites, indicating a higher filler load for the FA composites.

Table 3: Relative density and mechanical properties of the PVC composites

Filler loading	Filler	Relative Density (g/cm ³)	Milling direction		Transverse direction	
			Tensile strength (MPa)	Elongation at break (%)	Tensile strength (MPa)	Elongation at break (%)
30	CaCO ₃	1.3982	15.6 ± 0.7	232 ± 20	13.0±0.4	215 ± 12
	untreated FA	1.3763	14.3 ± 0.4	200 ± 10	9.8±0.4	148 ± 24
	4% SLS-FA	1.3745	15.2 ± 0.1	266 ± 5	13.7±0.2	206 ± 14
40	untreated FA	1.3988	10.1 ± 0.4	209 ± 8	9.3±0.5	143 ± 19
	4% SLS-FA	1.4034	13.4 ± 0.2	221 ± 11	10.5±0.3	153 ± 11
70	untreated FA	1.4691	9.0 ± 0.4	185 ± 5	8.7±0.3	111 ± 13
	4% SLS-FA	1.4772	9.4 ± 0.6	160 ± 2	9.7±0.4	144 ± 4

The tensile strength (Table 3) of the SLS modified FA-PVC composite was marginally higher compared to that of the untreated FA-PVC formulation. At a filler loading of 30 phr, the tensile strengths of the composites containing the CaCO₃ and SLS-modified FA fillers were found to be similar for samples taken in the milling as well as the transverse direction.

Elongation was observed to be significantly elevated for the 30 phr SLS modified FA-PVC composites but not for the corresponding 40 and 70 phr composites. SLS modified FA-PVC composites showed a higher resistance to pulling force in comparison to the untreated FA and CaCO₃ filled composites at 30 phr, while the untreated FA-PVC composite was found to have a significantly lower resistance to pulling force.

Alkan [3] reported that the tensile strength of a resin is expected to decrease with increasing fly ash content, which was confirmed by the tensile strengths observed for the 70 phr formulation in this study. The increased volume of fly ash particles in the PVC composites had a significant influence on the tensile strength as well as the elongation at break.

4. Conclusions

Although the chemical composition of the SLS modified FA investigated in this study was not altered extensively, significant changes could be observed in its physical properties. An increase in the temperature treatment of fly ash samples with aqueous surfactant solution resulted in increased surface coverage of the fly ash samples. From the results obtained, it is evident that further investigations need to be performed in order to fully understand the nature of the interactions between SLS and the fly ash surface. The occurrence of agglomerates on the surface of the SLS modified FA was confirmed by SEM and TEM, but its exact structure and composition is not yet known. Results obtained from FTIR and TGA-IR studies were promising in the sense that hydrocarbon fractions could be observed in the TGA-IR decomposition products. The possibility of interactions between fly ash and SLS were deduced from the FT-IR results of the solid samples, due to a small shift in peak positions of the S-O stretch, which may be indicative of electrostatic interactions rather than bonding interactions between SLS and fly ash. Wettability experiments confirmed that the hydrophilic FA surface was rendered hydrophobic after a change in surface properties of the modified fly ash sample.

Treatment of fly ash with SLS was found to be favourable for application in PVC composites, since an increase in tensile strength and elongation at break was observed for the TFA filled PVC, when compared to the PVC containing untreated fly ash at similar loadings. When considering only the strength and elongation tests, these results indicate that SLS treated fly ash can successfully replace CaCO_3 as filler in PVC when a low filler loading is used. However, these tests are preliminary and further research work need to be done to optimise the filler-PVC formulation.

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