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Investigation of Fuel Characterisation of Waste Sludge from Sewage Treatment Plants (STP)

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Abstract. Sewage treatment plants (STP's) throughout Malaysia are facing escalating issues on sewage disposable and environmental impact. Investigation on the sewage sludge for possible fuel formulation as renewable energy is being considered. The characterization of waste sludge on its volatility, High Heating Value and Energy output value will provide a preliminary finding for usage as potential biomass fuel. Co-combustion of sewage sludge and coal provide another formulation for potential biomass fuel depend on its technical viability and economical input.

1 Introduction

A research work involving the fuel sampling, characterization and fuel quality enhancement studies of dewatered sewage sludge was carried throughout Malaysia. The data obtained, analysis, options and potential application is yet to be implemented. The scope of work for the research was defined around the use of dewatered sewage sludge, available from treatment plants throughout Malaysia, as a potential fuel source for energy recovery through thermal treatment.

In general, the thermal treatment options available both commercially and under development can be summarized in Figure 1. The focus of this research, however, will be on the general fuel characteristics in preparation for its use as a solid fuel with the option to be co-combusted with other fuels such as coal.

The objectives of the study is to first establish a database of fuel properties of dewatered sewage sludge collected from the sewage treatment plants. Second, the potential for energy recovery through a thermal conversion process will be established. Finally, the feasibility of combining the dewatered sludge with coal (co-combustion) will be studied from a technical stand point. The key components and the respective standards of reference in the scope of work are listed as follows:

a) Sample collection and preparation (ASTM D346-90)
b) Fuel characterization (ASTM E1131-98)
c) Fuel quality enhancement (ASTM D440-86)

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The results obtained from the fuel characterization tests helped draw a few conclusions linking the treatment types and suitability of the samples as a potential fuel source. Based on the results from this work the options for energy recovery and the way forward will be further discussed.

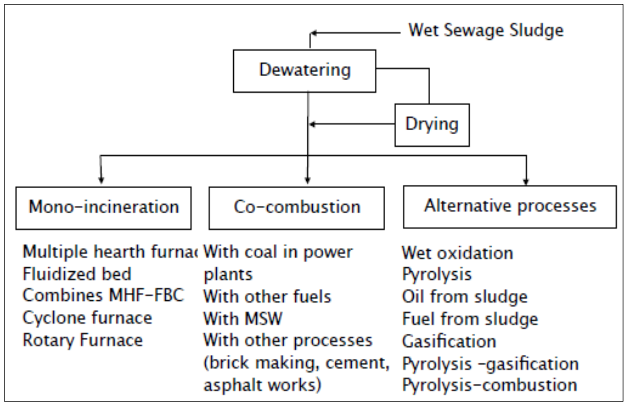

Fig. 1. Different routes of thermal processing of sewage sludge (adapted from [1]).

2 Test and Experiments

The specific experimental and testing procedures involved in the project is as follows:

a) Proximate Analysis: Moisture, Volatile Matter, Fixed Carbon and Ash
b) Ultimate Analysis: Carbon, Hydrogen, Nitrogen and Oxygen content
c) Higher Heating Value (HHV)
d) Rheology
e) Energy output analysis

As the properties of sewage sludge may vary considerably, depending on its processing and the operating procedures, repeatability of the above test were measured and presented as uncertainties in the final results. Each of these tests will provide the necessary data for an analysis to be carried out before a conclusion can be drawn in relation to the objectives of this investigation.

2.1 Proximate analysis

The proximate analysis is a standard test carried out to determine the fuel quality of a sample. The test was carried out in accordance to ASTM E1131-98 where it provides information on the amount of fixed carbon, inherent moisture, ash and volatile matter which are derived from the change in mass versus time of the sludge sample in a Thermogravimetric Analyser (TGA).

The TGA used in this study is a Perkin Elmer PYRIS1TGA which is available in the Mechanical Engineering Department, UTP. The sewage sludge sample weight which was tested in the TGA was set at 0.5g for each run and taken from three different depths in the standard 1.5- litre sample collection container used in this work.

The TGA tests were repeated for a total of five times in order to establish the uncertainties (precision and bias errors) in the measurements. Consistencies in the TGA testing protocols in relation to time factors were controlled by running each test within one week of its arrival from the STPs. A previous study by Ayoub, 2011 [2] on the effect of time on the fuel quality of collected dewatered sewage sludge was referred in coming up with the duration for the samples to be kept before testing is carried out.

2.2 Ultimate analysis

The ultimate analysis tests carried out in this work was done in accordance to ASTM D377-48 with a LECO CHNS-932 VTF900 machine available in the chemical engineering department, UTP. The amount of Carbon, Hydrogen, Nitrogen, Sulfur and Oxygen in the 0.1 g samples were measured using this analyzer. Similar protocol controls on external factors, sampling and uncertainty analysis were observed for the CHNS test. The tested levels of Nitrogen, Oxygen and Sulfur in the sample is used as a guide to the environmental impact of incinerating sewage sludge in relation to the Nitrus and Sulfur Oxides content in the flue gas.

2.3 Higher Heating Value

The heating value, also known as calorific value, is defined by the higher heating value (HHV), which is basically the energy content on a dry basis. The lower heating value (LHV) is calculated by subtracting the energy needed to evaporate the moisture content of the fuel. The presence of Carbon (C) and Hydrogen (H) tend to raise the heating value while Oxygen (O) decreases it. The HHV tests for this work were carried out in accordance to ASTM D-2015 using an IKA C5000 bomb calorimeter. 1g samples were placed in a crucible and instantaneously incinerated in the bomb calorimeter. The temperatures of water into and out of the equipment were measured and later used to quantify the amount of energy released. A calibration exercise with a standard benzoic acid sample is carried out before and after each set of test runs to measure the test accuracy.

2.4 Rheology

The drying of sewage sludge in its typical dewatering processes and for future use as solid fuels would require an understanding of the fluidic properties as far as the transportation of the substance is concerned. It has been found and reported in Werthers and Ogada [3], that the solid percentage increase in sewage sludge will cause the fluidic properties to be trixotopic or “sticky”. This will have an impact on the way the sewage sludge with the above mentioned solid consistency will have to be treated. In this work, a rheology study was carried out to obtain a first-hand understanding of this fluidic behavior in the samples collected. Samples from selected STPs were tested in a TA Instrument (RI AR-G2) rheometer to measure the viscosity of the samples with respect to its shear rate. The finding can then be correlated to the pumping requirements and other methods of transport considered for the material.

2.5 Energy output analysis

Apart from the data collected from the characterization tests for the available energy in sewage sludge, a more realistic measure of useful energy would be from a scaled down version of the fuel incineration facility. A 560 mm diameter x 320 mm high direct incineration chamber was fabricated for this project (shown in **Figure 2**.). This chamber has a water jacket with inlet and outlet piping for continuous flow of water and an infrared viewing window to study the burning rates of the solid fuels. The sewage sludge in this study were first dried, ground to 700 μm and compacted to form solid fuel briquettes as shown in Figure 3 (further details on the solid fuel preparation and design is discussed in the subsequent section). The solid fuels were then arranged in a tray and placed on the grate at the bottom of the combustion chamber. For each run, a constant solid fuel mass of 140g was maintained and arranged in a consistent formation. The incineration in the combustion chamber took place with a 1.6 air fuel ratio and at a fixed water flow rate of 2 L/min into the water jackets. The amount of combustion energy transferred into the boiler water was calculated based on the water flow rate and the inlet and outlet temperatures using the following equations and assumptions:

$$Q_{\text{briquettes}} = Q_{\text{water}} \quad (1)$$

and

$$Q_{\text{water}} = \dot{m}_{\text{water}}\, CP_{\text{water}}\, \Delta T \quad (2)$$

where, $Q_{briquettes}$ and Q_{water} are the energy from combustion components in watts, $\dot{m}$ water is the water flow rate in m3/sec, CP_{water} is specific heat of water in kJ/kg.K and ΔT is the difference in temperature of the inlet and outlet water (K).

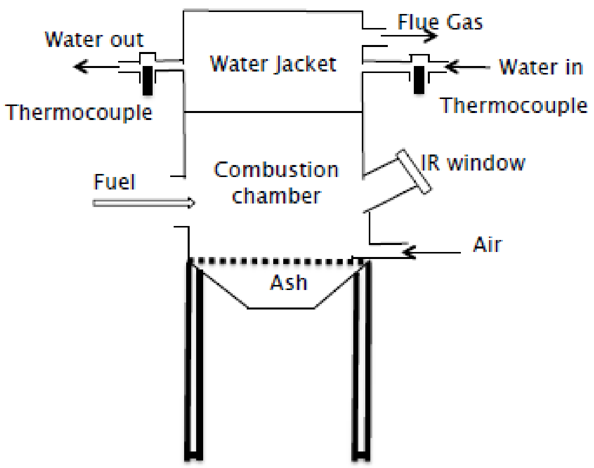

Fig. 2. Schematic diagram of the small scale boiler used for the combustion and burning rate experiments.

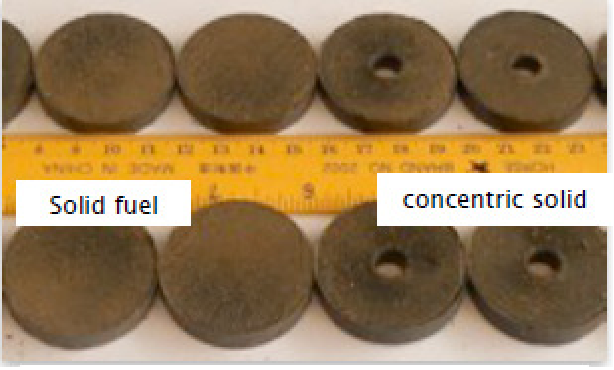

Fig. 3. Two solid fuel designs used in this study.

2.6 Solid fuel development

In the development of solid fuels it is inevitable that their mechanical properties are understood to address issues related to the transportation, storage and handling, especially when these fuels are used at locations which are of a certain distance away from where the fuels are made. The investigations carried out in this work involve exploring the solid fuel designs (to give the maximum exposure to combustion) and quantifying the fuel's compressive strength, stability, durability and water resistance.

There are a few key pre-treatment steps that were taken in preparing and treating the solid fuel prior to the respective combustion and mechanical tests. These steps include drying, grinding and densification (briquetting). After drying, the samples are pulverized and sieved to maintain an average particle size of 700µm (selected size based on nominal value used by previous researchers).

The binding material selected for this work is the inherent moisture available in the sewage sludge samples; previous work suggests the use of materials such as paper, starch, fibre etc. The densification process involved the use of a hydraulic compacter (press) with two mould options, a solid cylinder and a ring type cylinder. The two designs were selected to test the effect of exposed surface area on the burning and combustion of the solid fuel. 10g of sewage sludge were densified to produce solid fuels of 40 mm diameter x 10 mm height. The solid fuels produced in this research were compacted using a uniaxial 25 ton CARVER, INC. automatic pellet press as shown in **Figure 4**. The bottom part of the mould was placed in the base plate of the pressing device while the top part of the mould (piston road) was connected to the crosshead by a 50mm-diameter compressive cylinder connection.

Fig. 4. Densification press for solid fuel fabrication.

2.7 Co-combustion test

Co-firing or co-combustion is the simultaneous combustion of two or more fuels in the same facility in order to produce one or more energy carriers. Co-firing biomass with coal in existing boilers costs about 2-5 times less to implement than other bio-electricity generating options and is also in the lower cost range compared to other renewable energy based electricity options [10]. The co-combustion of sewage sludge with coal has been previously studied by numerous researchers. The advantage of the coal-sewage sludge combination is the large reduction in volume of sludge as well as the thermal destruction of toxic organic compounds and pathogens.

The disadvantage, however, is the emissions of NOx (due to the relatively higher content of N2 in sewage sludge as compared to coal), dioxins and trace elements. Nonetheless the high volatile content in sewage sludge accelerates the air consumption in combustion, diminishing the rate of Oxygen/Nitrogen (O/N) in the flame, and represses the thermal gradient of NOx. With commercially available adsorption mechanisms, up to 90% of these environmental threats can be easily removed. The TGA procedure carried out in the previous sections will provide the necessary reference in dealing with the disadvantages in thermally treating the sludge for energy recovery purposes.

3 Results and Discussion

3.1 Fuel characterisation

3.1.1 Proximate and Ultimate Analysis

The proximate and ultimate analysis were important measures of the fixed Carbon, Hydrogen, Nitrogen, Sulphur, Oxygen, volatile matter, inherent moisture and the amount of ash present in the fuel sample. A fuel which has high oxygen content is most likely to cause an increase in combustion reaction rates whilst high ash content in the fuel mixture has the opposite effect. A high volatile matter removal rate will speed up combustion but at the expense of losing out on un-burnt fuel to sustain combustion for a longer period of time.

The presence of Nitrogen and Sulphur in the fuel content may raise concerns over the emissions of harmful gases. A compilation of the proximate and ultimate analysis results for the samples collected from the participating STPs is shown in Figures 5 and 6 for discussion purposes.

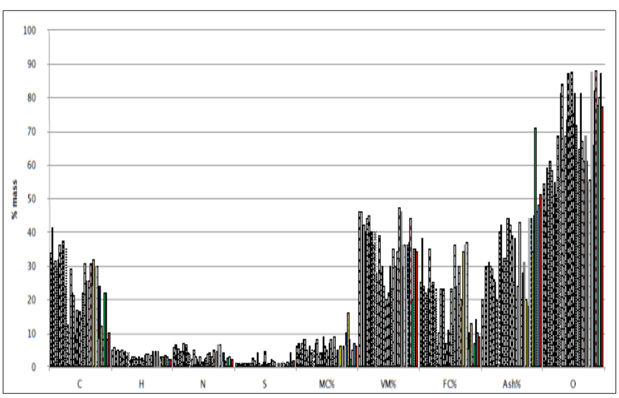

Fig. 5. Ultimate and Proximate analysis of 50 sites.

The ultimate and proximate analysis results show the spread of elements (Carbon, Hydrogen, Nitrogen, Sulfur, Oxygen, Ash, Volatile matter and Moisture) which is present in the sewage sludge sample. The high carbon content, related to good fuel properties, in certain locations are representative of highly populated urban areas. The link between sewage sludge collected from city dwellings, eateries and commercial locations to high carbon content was also observed and reported from studies carried out by different researchers at a variety of locations worldwide [11-14].

Besides Carbon, there are several factors which can be attributed to the higher energy yield of the samples collected from sites with different demographic make-up as well as possible sludge treatment types and practices. The existence of plastic components in sewage sludge samples were linked to areas within city limits and with light to medium industrial activities by Barneto (2009).

Plastic or polymeric substances are known to contribute towards a high energy yield during incineration but at the expense of additional environmental cleanup facilities. Further investigations will be required to determine the plastic or polymer content in the samples collected from the urban/city STPs before a conclusive finding can be made as to the contribution of specific components towards high HHV readings in base on collection areas. The observations made from the results of the current study also comes from the treated sludge disposal procedures at the respective STPs.

Some of the STPs practice a quick sludge removal cycle for their dewatered products which suggest a low residence time before disposal, whereby in this study, represents minimal degradation of the samples prior to testing. A comparison made between the average values of the ultimate and proximate analysis results and published values of hard coal is shown in **Figure 6**. As expected the value of carbon and fixed carbon (FC) for coal supersedes the amount available in sewage sludge.

The high ash and Oxygen content in the samples when compared to coal is to be expected of sewage sludge. The oxygen component will help combustion reaction whilst the ash component has a negative effect. The levels of Nitrogen and Sulfur, which is known to have a negative environmental effect, seem to be at par, if not only slightly higher than coal. On the average, the differences in volatile matter (VM) content in the samples were rather small in comparison to coal.

The presence of a high VM content will result in high activation energy, a quantity much searched for to enhance the burning of solid fuels. This will also be an attractive factor for co-combustion strategies as the component with high VM will enhance the early burning of the solid fuel to kick-start the energy released from the combustion process. A closer investigation of the individual data will point towards the samples collected from the urban areas having higher VM than the average, hence suggesting the suitability of sewage sludge from these areas to be converted into solid fuels in combination with conventional fuels such as coal.

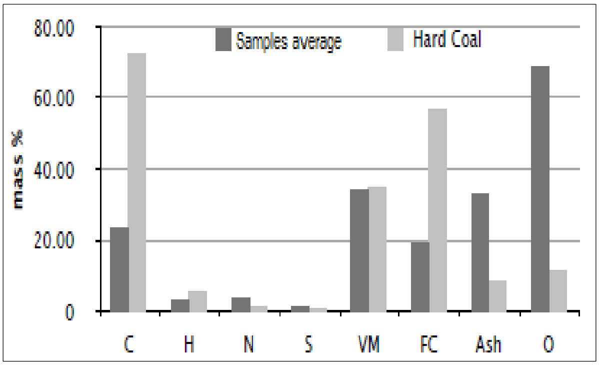

Fig. 6. Figure 6: Comparison of the average proximate and ultimate analysis results with coal [Th. Gerhardt].

3.1.2 Higher Heating Value (HHV)

The higher heating values of the collected samples are shown in **Figures 7**. As the HHV is a very good indication of the suitability of a proposed fuel, from the available energy standpoint, a comparison of the regions and treatment process were made and discussed in this section. A close examination of these locations would reveal than the STPs with the high HHVs in certain regions were surrounded by commercial activities such as eateries, light industrial plants and densely populated surroundings.

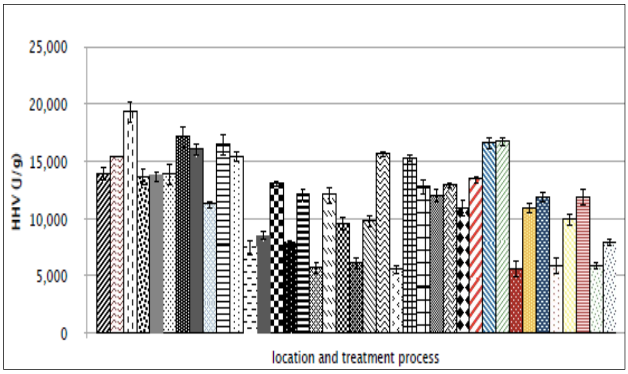

Fig. 7. Comparison of higher heating values (HHV) for the different collection of location and treatment process.

The locations with higher population and surrounded by commercial activities were noticed to benefit from a faster sludge disposal process. The samples that were collected from these locations had very short settling time as compared to the locations which employed open bed drying.

Nonetheless, there were certain exceptions such where some areas which dried their dewatered sludge in an open bed facility but still recorded relatively high HHVs. In general, the sludge samples, which underwent a somewhat rigorous dewatering process and were left to settle for a relatively short period of time showed signs of good fuel properties.

In comparison with data collected from previous research work carried out on worldwide locations, the HHV values samples studied were reasonably fair**. Figure 8** show where the Malaysian samples stand in comparison with samples tested from sewage sludge from other locations and that had undergone different types of stabilization process. Also shown in this figure is the nominal HHV for power plant grade coal.

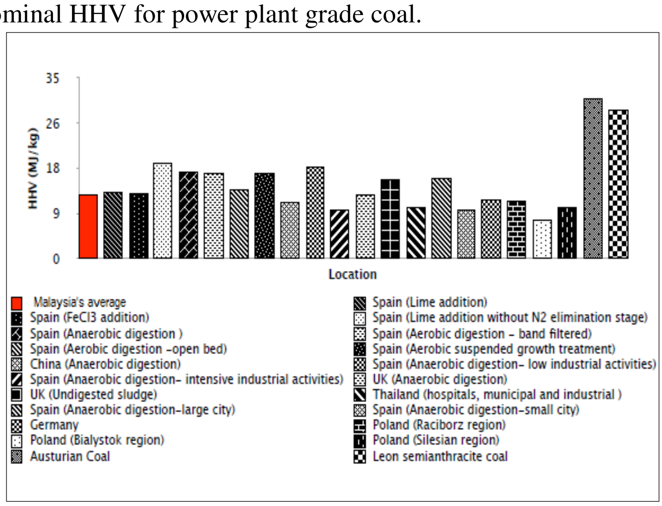

Fig. 8. Comparison of higher heating values (HHV) for worldwide locations.

Apart from the very unlikely anomalies, considering the reasonable uncertainty range for the measurements reported in this study, the data presented here can be used with a high degree of certainty.

3.1.3 Rheology

The measurement of viscosity of the wet sludge against its shear rate is an indication of the non-Newtonian behavior or “sticky” appearance of the sample. This is an important consideration for pumping and transportation purposes. The test carried out for the samples were however quite difficult to characterize for its thixotropic behavior. The results obtained, as shown in **Figure 9**, show a region in which the measurements were able to predict the relevant properties (shear rate less than 1). A rheological comparison with water show the relative pumping requirements for sewage sludge. The area in the graph which can be used to indicate relative pumping power is for shear rates below 1. Further investigation on the rheological properties is required before a complete analysis can be carried out and a firm conclusion can be drawn. This study is especially useful for the transportation of wet sludge into the drying facilities and may provide an indication of the degree of back-drying required to facilitate the movement of this material.

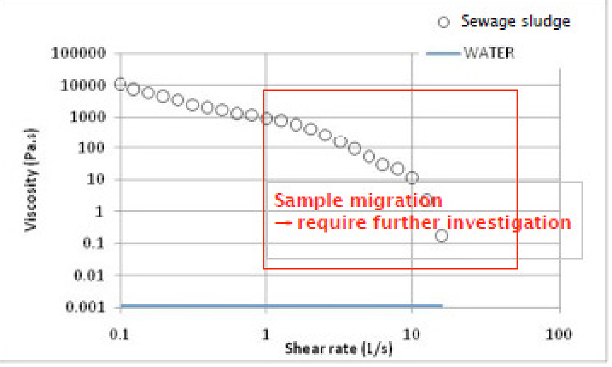

Fig. 9. Rhelogy results for sewage sludge samples.

3.1.4 Energy output analysis

The amount of available energy which was able to be harvested is indicated in this section of the report. The test for available energy was carried out with solid fuels fabricated from dried and pre-treated sewage sludge as discussed earlier in section 3.6. Figure 10 illustrates the potential energy released based on the inlet and outlet water jacket temperatures with respect to time. Also shown on this same graph are the flue gas and combustion temperatures.

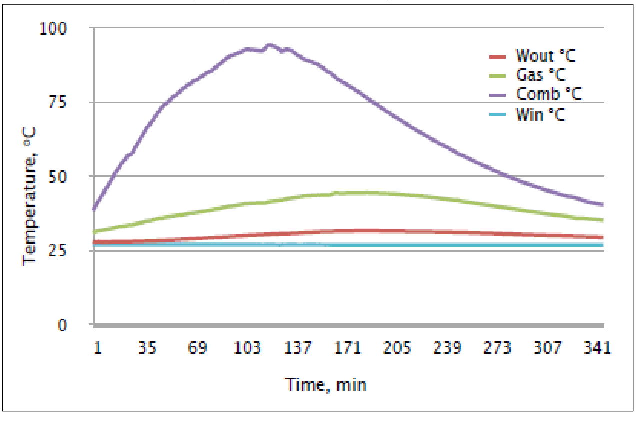

Fig. 10. Energy output from burning sewage sludge solid fuel samples.

The total available energy released, based on the measured water temperatures and properties, was found to be 3.14 kWhr/kg of solid fuel burnt. An important observation from **Figure 10** is how the peak temperatures lasts for a short period of time before a drastic reduction takes place, in the case above, between 100 – 150 seconds. This trend is apparently typical for sewage sludge as the material contains high volatile matter and Oxygen compared to conventional fuels such as coal. The result of co-combusting sewage sludge with coal, which is an extension to this energy output section, will be discussed in the subsequent sections.

3.2 Solid fuel development

The enhancement of sewage sludge as a fuel source was proposed under "solid fuel development" by (a) fabricating solid fuel briquettes and (b) mixing sewage sludge with a conventional solid fuel such as coal for co-combustion.

3.2.1 Mechanical strength

The compressive strength, durability, immersion and SEM tests were successfully carried out on the solid fuel briquettes which were dried and pressed into shape. Two solid fuel designs were explored, a solid cylinder and a concentric cylinder (with hole). The compressive strength test indicate that the solid fuels are able to withstand as much as 13.8 and 12.6 MPa of pressure for the solid and hole designs respectively. The similar strength test was repeated for oil palm waste to provide some form of reference for the sewage sludge fuels. The oil palm fuels were found to be able to withstand almost similar compressive pressures at 14.9 and 12.6 MPa for the solid and hole designs respectively. The stability of the sewage sludge solid fuels, measured in terms of the percentage of its shape retained after a period of time, saw the sludge samples loose only 0.7% of its original shape after 21 days.

The observation made for oil palm waste solid fuels found them to be less stable in that they lost more than 2% of their size for the same test duration. The durability of a solid fuel is measured from the percentage of mass loss after a drop test is carried out. In this test, the sewage sludge solid fuel lost close to 6% of its original mass whilst the oil palm fuels lost about the same amount. It is worth noting that the mechanical tests have so far proven that sewage sludge solid fuels have good potential for transportation, storage and handling if it were to be explored for commercial applications.

A further test to check the reasons behind its strength is by running it through SEM. The following SEM images were taken on the surface of the solid fuel samples after it had been sheared off in the mid-section. The oil palm solid fuel was again used as a bench mark in qualitatively comparing the results of the SEM test.

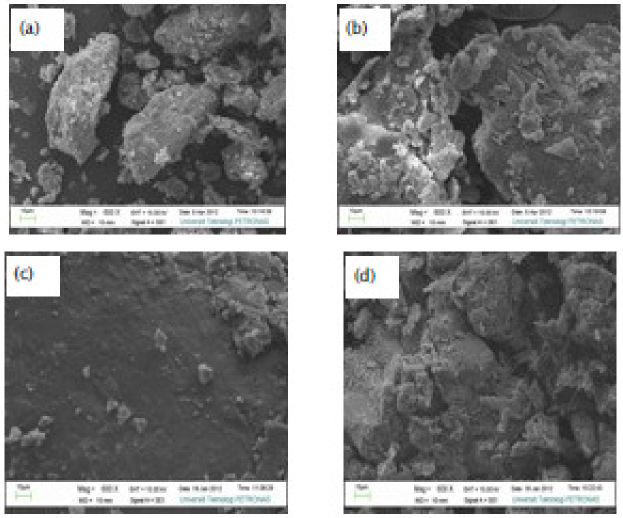

Fig. 11. SEM test results for sewage sludge (a) and (c), and oil palm (b) and (d).

Figure 11 show the SEM images of sewage sludge and oil palm samples before (a & b) and after (c&d) they were pressed. Sewage sludge show a less porous microstructure compared to the oil palm samples. This observation supports the earlier test results for compressive strength stability and durability as it shows how the sample particles are more intact and less porous compared to oil palm.

The reasons for this is believed to be linked to the inherent moisture content in sewage sludge which act as a binder that bridges the solid particles, after they are all pressed together. The oil palm fuel on the other hand relies on its longer fibre lengths and limited amount of inherent moisture to help bind the fuel particles together.

3.2.2 Co-combustion

The quality of the sewage sludge fuel can be further enhanced from an energy and emissions point of view by mixing it with other biomass waste/conventional fuel material such as poultry processing waste, coal, oil palm fibre etc. UTP's past research experience and the internally generated database on biomass waste fuel properties suggest a potential for fuel quality enhancement by mixing sewage sludge with the above mentioned material. For the scope of work identified in this research work, only coal will be considered in this preliminary assessment of co-combustion with sewage sludge. Co-combustion with coal, in particular, is more economically viable considering the limited supply and price increase of coal in recent times. From the technical point of view, the sewage sludge component can complement the burning of coal in that it can sustain combustion over a wider temperature range; sludge combustion starts at a lower temperature due to the early volatile liberation and can assist the coal combustion when it is in a mixture. The energy released when incinerating sewage sludge and coal in sewage sludge to coal ratio of 10:90, 30: 70 and 50:50 is shown in Figure 12.

Although it may be desirable, from the available energy point of view, to use the 50:50 co-combustion ratio, other factors such as the environmental effects (NOx and SO_2 from sewage sludge) and the high ash content in sewage sludge will have to be considered. Previous works by other researchers have suggested a sewage sludge contribution of only 10-15 % in the combustion mixture to address the concerns highlighted above. The other reason for limiting the sewage sludge contribution is due to the high volatile matter (VM) in the sludge which allows the sludge to react or burn faster than coal. This will cause some instability in the burning profile of the fuel if too much VM is allowed to be present.

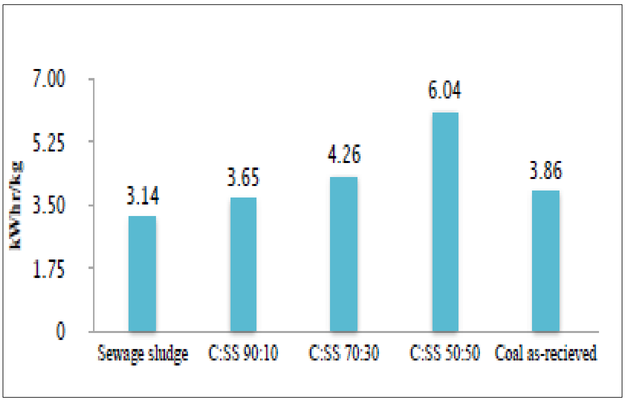

Fig. 12. . Energy released for co-combustion of sewage sludge and coal.

4 Conclusion

Through the tests and experiments carried out in this project sufficient amount of data have been collected and analyzed. A database of fuel characteristics have been established for dewatered sewage sludge originating from different regions in the country and for a variety of STP processes. The ultimate and proximate analysis was able to identify the key components in the fuel which can be further explored to select the appropriate thermal treatment route towards energy recovery.

Based on the data generated in the investigation, the sewage sludge has amounts of fixed carbon which are comparable to samples tested from other parts of the world. The volatile matter and Oxygen content is generally high which is an indication of good combustion reaction. The Nitrogen and Sulphur levels were reasonably low and their effect on the emissions can be easily managed by existing technology.

The higher heating values were useful in first, identifying a base value for the available energy which can be recovered and second, linking the process and regions which are most viable for an energy recovery project to be implemented. The solid fuel development work within this project was able to create options for utilizing the sewage sludge in the form of ready-made fuels.

The technical and economic viability can be made more attractive if co-combustion, in particular with coal, is pursued. Based on the findings from the current work, further areas which can be explored include:

1. Solid fuel development: transformation of raw waste into commercially viable products for sale to power generation facilities.
2. Co-combustion options with other biomass materials: sustainability of supply, pre-treatment feasibility, energy output and environmental problems mitigation.
3. Feasibility studies relating to energy recovery from sewage sludge on a larger scale (pilot plant): Drying, storage, handling and efficient combustion methodologies.
4. Economic analysis on the options to pursue a solid fuel development plant, to supply raw sewage sludge for the co-combustion with existing solid fuels or to become an IPP based on the attractive FIT tariffs currently offered by the government.

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