IJAAR PUBLISHING®

Engineering Research Journal | ISSN: 2782-8212
Vol. 6, Issue 2 (2026) | www.ijaar.org/erj

EXPERIMENTAL STUDY OF SELF-IGNITION COMBUSTION OF COAL AND MEANS OF SUPPRESSING IT

BY

Nwankwo Nnaemeka H. and Ani Moses C.
[1&2]Department of Mechanical Engineering Technology, Federal Polytechnic, Oko
Email: nwanc2004@gmail.com, 08068819721

ABSTRACT

Combustible solids may self-ignite during mining, storage and transportation time andeven in industrial plants. The self-ignition process may be slow and unnoticed and there are several accidents in mines, and in industrial plants as a result of unnoticed slow self-ignition heating of fuels like coal, peat, and saw dust. This study investigated self-ignition combustion of coal with emphasis on the process, factors, and means of extinguishing or suppressing the smoldering fire after ignition through a small scale experiments as a representative of similar solid fuels that behave alike. The self-ignition data from experiment was computed and parameters like moisture content, pore volume, density and temperature of ignition were recorded. Suppression agents were discovered and also compared with time of quenching. Gaseous N_2 and CO_2 were found to be most suitable for extinguishing the coal fire and smoldering of coal under open and closed geometries. The suppression time in different ventilation circumstances and agents in bottom, top, open and closed vessels of the experimental apparatus were studied and all differs. This work is useful to scientists, fire fighters, industrial users, and especially the coal mining industry.

Keywords: Coal, Suppression agents, Self-ignition, temperatures and Moisture content

Nwankwo, N. H., & Ani, M. C. (2026). Experimental study of self-ignition combustion of coal and means of suppressing it. *Engineering Research Journal. 6*(2), 1-12. https://doi.org/10.46654/mxydxn49

INTRODUCTION

A lot of research has been done on coal with less attention to the self-ignition combustion of coal in Nigeria and how to extinguish the resulting smoldering fire. Also, guidelines for extinguishing the self-ignited fires in industrial plants in Nigeria have not been much elaborated scientifically by theoretical and experimental means. Nigeria in trying to diversify its power source and energy generation must be involved in increased mining activity to support the petroleum which is commonly used. This paper tried to discuss self-ignition combustion of solid coal to provide useful information for miners in Nigeria to check hazards, explosions and as well educate the coal miners and scientists involved in coal storage, transportation and usage in open and closed vessels.

Concept of self-ignition and spontaneous combustion

Self-ignition of coal means the onset of exothermic chemical reaction and a subsequent temperature rise within the combustible material without the action of an additional ignition source. Spontaneous combustion of coal on the other hand, is the process of self heating resulting eventually in its ignition without the application of external heat. When coal is exposed to air, it absorbs oxygen at the exposed surface. Some fractions of the exposed coal substance absorb oxygen at a faster rate than others and the oxidation results in the formation of gases, mainly CO, CO_2, water vapour along with the evolution of heat during the chemical reaction. The process takes place at normal temperature, but it is slow and the heat evolved is not carried away by air. If the rate of dissipation of heat is slow compared with the evolution of heat by oxidation, there is gradual build up of heat and rise in temperature reach the ignition point of coal which then catches fire (Ohlemiller et. al, 1983)

Factors contributing to self- ignition of coal

Aside from natural affinity of coal to self heating, a number of factors are significant when studying self-ignition combustion of coal. Some of these factors are: moisture content, coal rank, available air, particle size and surface area, methane content, physical properties, minerals and so on.

Moisture: Samples of coal have been tested to determine the self-ignition rate of the coal at various moisture contents ranging from as-received to fully dried. These samples containing varying amounts of moisture experience different rates of initial self-heating, with some moist samples oxidizing at a faster rate than the dry samples.

Coal rank: The tendency of coal to self-heating decreases as the rank increases. As rank decreases, inherent moisture, volatile matter and oxygen and hydrogen contents of the coal increases which in turn increases the oxidation. Moreso, lower rank coals often have a greater porosity than higher rank coals and therefore more surface area is available for oxidation. Also, low rank coals contain long chain hydrocarbon making them less stable than lower hydrocarbon component (Walters, 1996).

Available air: Small amount of air makes rate of oxidation very slow and large quantities of air passing through the coal caries any heat produced away so that temperature does not rise. However, between these two limits, there is a

state when air is sufficient to promote oxidation but not sufficient to carry away the heat formed, so that there is an accelerating rate of oxidation until ignition occurs.

Particle size and surface area: A comparison with coal particles of various sizes showed that the smaller particles seem to have lower alkane than the large particles (Bannerjee, 1985). Oxidation increases with increasing fines of coal .and the rate of oxidation of coal with oxygen of air is proportional to the specific internal surface area.

Physical properties: A number of physical properties such as porosity, permeability, hardness, thermal conductivity and specific heat can influence the rate of oxidation and thus result in self-ignition combustion. The rate of heat transportation from the coal depends on its thermal conductivity. Coal with low thermal conductivity tends more frequently to spontaneous combustion.

MATERIALS AND METHODS

Source of samples

The coal samples used for the test work were taken from a stockpile at Orji-River power station Enugu, Enugu state. The sample was sent to mechanical engineering laboratory, Federal Polytechnic, Nekede, Imo State for analysis.

Preparation and Testing of Samples

The coal was split into six 250g samples of 30mm coal and placed into frozen storage until they were required for testing. Prior to testing, each 250g sample was ground and screened to produce 150g of 212mm coal and flushed under nitrogen. The first test, sample 1 was prepared and tested under normal R70 conditions (dry basis) which required the test sample to be dried at 110^{OC} for 16 hours. After this, it was transferred to the adiabatic oven and the test commenced from a start temperature of 40^{OC}. A full description of the adiabatic testing procedure is outlined by beamish, Barakat and St George (2000).

The remaining tests were conducted at varying moisture contents to investigate the effects of moisture contents on the self-heating rate from a start temperature of 25^{OC}. To do this, the drying times in the laboratory oven were varied as required to allow the coal sample to attain the desired moisture content.

Test apparatus (small-scale)

The small-scale tests were arranged in a schematic drawing of the basic test apparatus shown in figure 1. It consists of an open, cylinder-shaped chamber of approximately $1.3dm^3$ of volume. A gas inlet in the bottom of the chamber provides the suppression agent into the chamber over its total cross-sectional area. The thermocouples in the chamber read the temperature of the samples. The heater in the centre of the chamber supplied heat to the sample. The copper tube on the right-hand side is used for pressure measurement.

In a few tests, the chamber was covered with a cylinder that left a 3cm high empty volume above the top of the sample surface. In the cover, there were two approximately 2cm wide holes to provide exits for the smoke and inlets for fresh air. With the cover on,

gaseous agents could also be fed into the chamber from above. Photographs of the open and closed geometries are shown in figure 2 and 3 respectively.

Procedure for the Ignition and Suppression Tests of the Coal.

The small-scale tests were conducted in open and closed geometries respectively and the ignition procedure was always the same for both geometries. For igniting the coal, pilot ignition was applied, i.e. a heater wire was applied. The 7.5cm long wire (heater) was overloaded with a power of 400W/M for 30 min, which was sufficient for igniting the tested materials. The generated smoldering fire was allowed to proceed freely for a further 60min. The active suppression procedures were started and continued till the temperature at each measurement location had reached a value below 150^{OC}. The development of temperatures was further recorded to see whether the sample re-ignites or extinguished. Up to six thermocouples distributed in the chamber indicated the temperature conditions inside the material.

Instrumentation

Temperatures were measured with K-type, ǿ0.5mm bore thermocouples. Setra Model 264 Pressure Transducers were applied in pressure measurements. The oxygen concentration was measured with a Siemens Oxymat 5E analyzer of paramagnetic type. The mass loss was monitored throughout the test with a Load Cell. Gas flow was adjusted and maintained using a flow meter. Datas were recorded continuously duringthe tests with a Solartron 35951C I.M.P. data recorder connected to a 386 PC micro computer.

EXPERIMENTAL ARRANGEMENT OF IGNITION AND SUPPRESSION TESTS

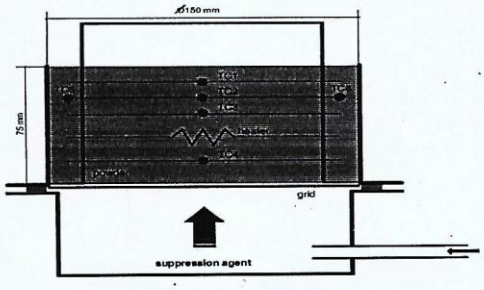


FIG 1. Experimental schematic arrangements

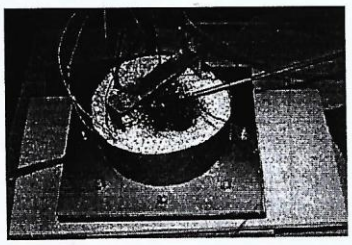


Fig. 2 Open Geometry picture of experimental set up

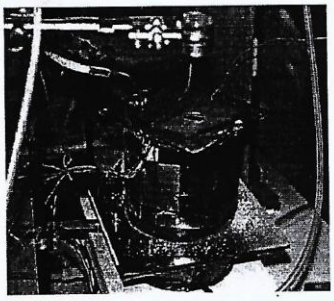


Fig. 3 closed geometry picture of experimental set up

RESULTS AND DISCUSSION

Moisture contents for the samples 1-5 replicates are contained in table 1. These are approximates for fully dried coal; 25% as- received moisture; 50% as-received moisture; 75% as-received moisture; and approximately as-received moisture.

TABLE 1

Test sample	As-received Moisture (%)	Test Moisture Contents (%)
Sample 1	24.3	0.0
Sample 2	24.3	7.3 -
Sample 3	24.3	12.5
Sample 4	24.3	16.5
Sample 5	24.3	24.0

TABLE 2

Test Sample	Test Moisture Contents (%)	Initial Self Heating Rate (°C/h)
Sample 1	0.0	12.92
Sample 2	7.3	21.62 .
Sample 3	12.5	17.07
Sample 4	16.5	16.07
Sample 5	24.0	10.87

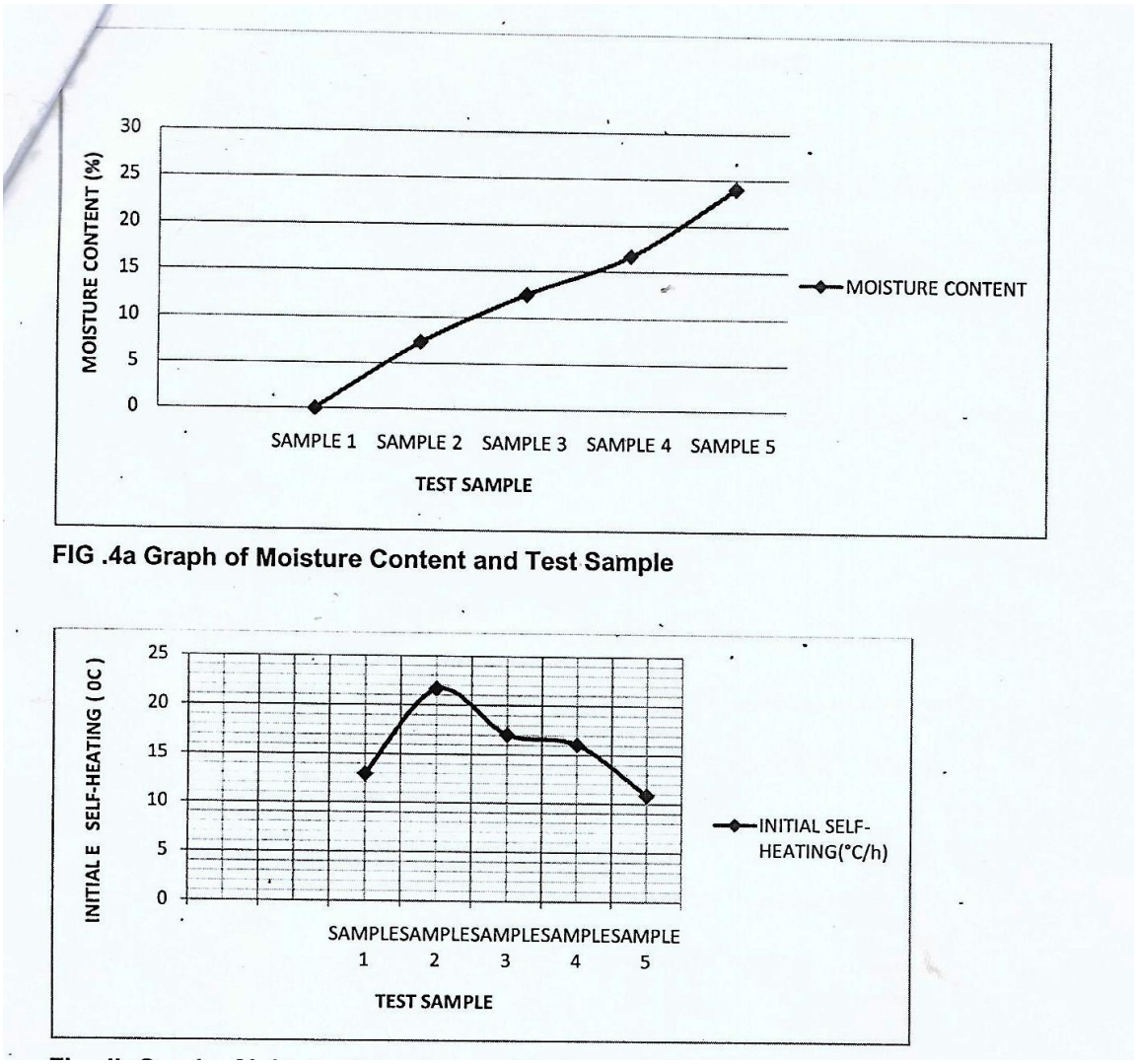


FIG .4a Graph of Moisture Content and Test Sample

Fig. 4b: Graph of initial self-heating and test samples

A value for the initial self-heating rate (from the room temperature start through to70°C), has been calculated for each of the coal moisture states (Table 2). The initialself-heating rate curves for the samples 1-5 replicates are shown in figure 4b. The sample 2, test sample containing 7.3% moisture (fig. 4a), has the highest value of all the tests. This suggests that there is optimum moisture content for the coal where the initial rate of self-heating is considerably enhanced. Itis also evident from figure 4b that even the sample with 75% of the as-received moisture content (sample 4) had a higher initial self-heating rate than the dried coal. Also, Close to as-received moisture content (sample 5) had slower initial self heating rate than the dried, coal.Work by Clemens and Matheson (1996) on the relationship between initial self-heating rate and moisture content attributed the increased self-heating of the moist coal to the presence of tightly bound moisture generating radical sites in the coal (where oxidation occurs) that are more reactive than those derived from fully dried coal. Also, Vance, Chen and Scott (1996) attributed the sample with close to the as-received moisture content having slower rate of initial self-heating than the dried coal to the fact that moisture can block the access of oxygen through the coal pores making the oxidation slow.

Burning of the Samples

The burning rate of the coal samples was extremely slow especially in the open chamber with originally some 250g of coal, only less than 10g was consumed during the first 90mm. the ignition temperatures are recorded in table 3. Figure 5 shows the temperature curves measured during the test.

Table 3: Ignition Temperature Recorded During Coal Combustion

Time (Min)	Ignition Temperature (^{0}C) TC_1	TC_2	TC_3	TC_4	TC_5
10	15	20	100	300	11
30	75	90	300	510	72
50	70	83	230	231	70
70	65	100	260	200	65
90	68	110	180	180	68

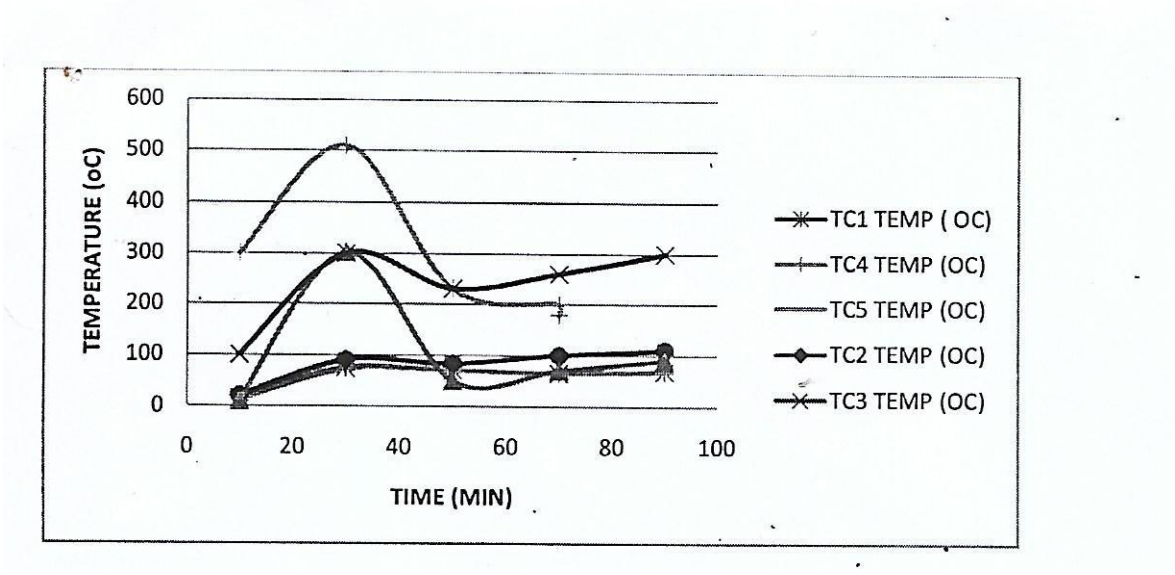


Fig. 5 :Graph of ignition temperature and time for thermocouples TC1-TC5

Tc_1-TC_5 represents the thermocouples that recorded coal ignition temperatures. Forigniting the coal sample, the heater was on for the first 30min, followed by further 60min of free burning and thereafter, suppression was started at 90min. from the graph (fig. 5), highest ignition temperature was recorded by thermocouple, TC_4 followed by thermocouple TC_3. After 30min, temperature decreases slowly showing the free burning

after ignition.

Grain Size and Pore Volume of Samples

The coal samples were sieved with a continuously operating Sweco Shaking sieve (diameter 700mm). The pore volume of the samples was determined by Micrometrics pore sizer 9300 mecury porosimeter. The pore volume increases with increased grain size. A few self ignition temperatures were determined to define the limiting temperature for the suppression tests, at which the fire could be judged to have been extinguished. The self-ignition temperatures were determined in accordance with the Nordtest method (NT Fire 045 NT, 1992) and (Bjorkman et.al, 1992). The self-ignition temperature reduces whenever there is an increase in the sample -pore volume. This can be seen in figure 6.

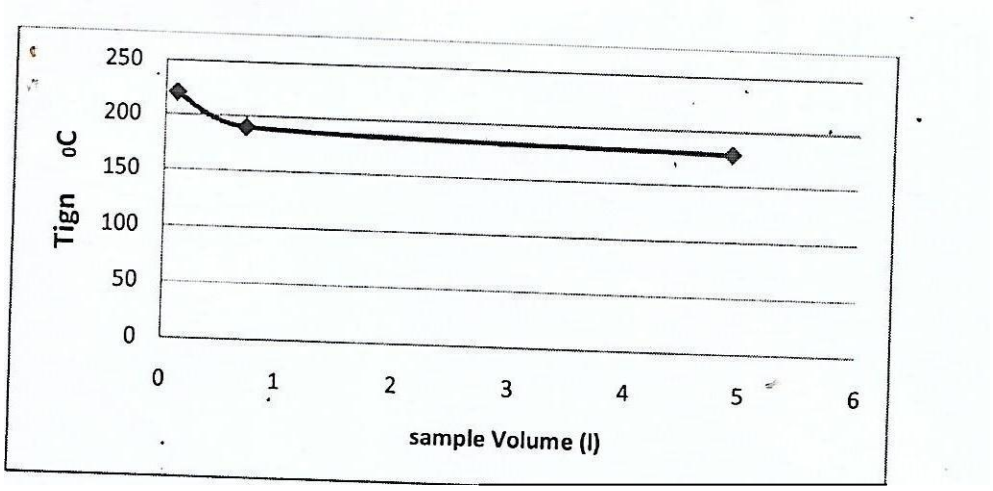


Fig. 6: Graph of Ignition temperature and sample volume

Based on the results above, the safe limiting temperature for small-scale tests was takento be 150°C, at which active suppression procedures were stopped (NT FIRE 0.45NT, 1992) and (Bjorkman et. al, 1992). It should be noted/however, that lack of information on the properties of the burned material makes it difficult to estimate what would be a truly safe temperature to stop the suppression measures.

Suppression Agents

Possible suppression agents include at least the following agents: gaseous Na, gaseous CO_2, Ar and other commercial inert gas mixtures and water with and without additives. The performances of these agents in the suppression process were chosen to be studied in a systematic way. The most promising suppression agents in closed type applications are the gaseous agents, which have proven to be successful in real fire fighting. The traditional gases N_2 and CO_2 were taken as the agents of practical importance. Ar and its inert mixture (with a density between the N_2 and CO_2 densities) may be expected to behave in a similar way.

TABLE 4: Suppression Agents in Open and Closed Vessels and Extinguishing Time

IDENTIFICATION	N_2,b,0	CO_2,b,o	N_2,b,c	CO_2,b,c	N_2,t,c	$C0_2$,t,c
TIME (MIN)	70	42	18	15	31	27

b, o=bottom openb ,c = bottom closed t,c = top closed

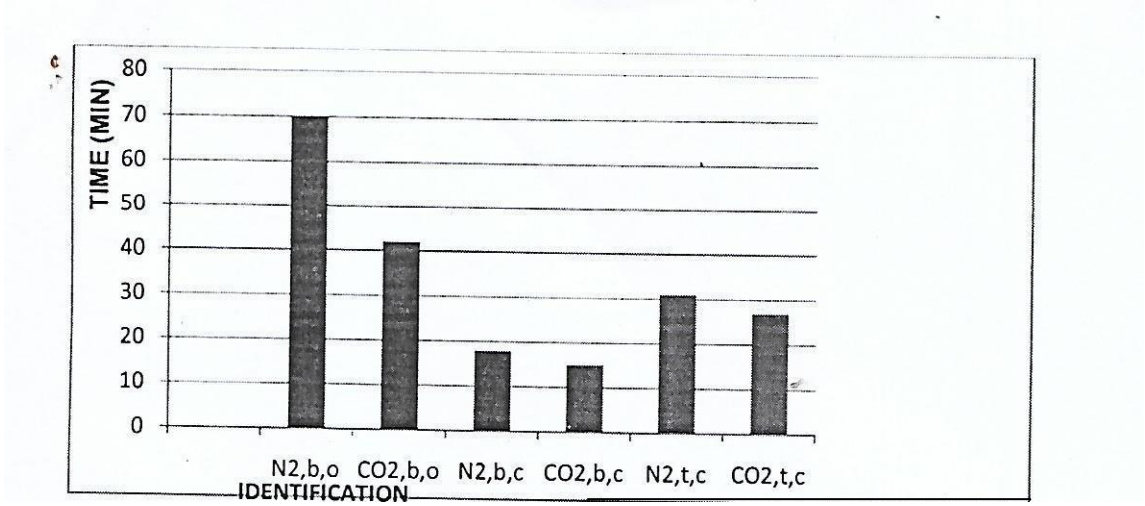


Figure 7: Suppression time in different ventilation circumstances Identification is as follows: suppression agent, feeding port (bottom, top), chamber type (open, closed).

Comparison tests with N_2 and CO_2 were run both in the open and enclosed geometries. With the cover on, the agent was fed either from below or from above. The flow rate was 0.5L/Min, so as to minimize any possible differences. The relevant results are shown in figure 7. In each case $CO_2$was more efficient in extinguishing the fire than N_2. This is because it took lesser time during the suppression tests as shown in figure 7. Obviously, due to its higher density, it was better retained in the sample.

The most efficient way of injecting gaseous agents is from below. Due to the upwards flow in a fire situation, the oxygen necessary for the smouldering will flow into the smouldering material primarily from below and will gradually be replaced by the gaseous agents.

CONCLUSION AND RECOMMENDATION

Conclusion

The testing of highly reactive sub-bituminous coal from Enugu in a closed and open chamber shows that a maximum initial self-heating rate occurred at approximately 25% of the "as-received" moisture content and that the dried coal sample exhibits higher initial self-heating rate than the sample with highest moisture content(close to asreceived moisture content). These findings suggest that increasing the moisture contentof this coal would not eliminate the risk of the coal self-heating whilst being transported and stored but the self-heating data does indicate that keeping the moisture content of the coal high will increase the time to ignition. This would have to be considered on a cost benefit basis, and clearly the simplest solution is to use the

coal as soon as possible.

Out of the five different suppression agents suitable for suppressing coal fires "CO_2 Vs N_2" were the major issues discovered in the tests. The small scale tests indicate that CO2 is more effective than N2 because of its higher density.

With this study, useful information has been provided for: Fire fighters to control fire in open and closed vessels during mining activities, thermodynamic scientists concerning coal combustion, developing useful fire extinguishers which will act on ignited materials and reduce fire spreading and the Nigerian Raw Material and Research Institute to develop the mining safety programme for coal mining and other solid minerals.

Recommendations

- To The Nigerian raw material and research institute in other to develop the mining safety programme for coal mining and other solid mineral.
- To designers for building services design, installation and fire control.
- Recommended for developing useful fire extinguishers which will act on ignitedmaterials and reduce fire spreading.
- Prior to taking any active suppression measures, all the possible openings shouldbe closed, the tighter the enclosure is the better.
- Also, prior to and during suppression, any whirling up of the powdered materialshould be avoided to prevent potential dust explosions.
- Temperatures should be monitored at several locations around the centre of anyclosed chamber (or at any other known hot spot) over extended periods of timebefore opening the chamber.
- Oxygen concentration should be monitored in the empty space above the storedmaterial. The concentration should be maintained low (preferably below 10%, butin any case below 15%) for a sufficiently long time.
- The coal mine sites should be equipped with a suitable fire detection system thatalso monitors the suppression process.

REFERENCES

Banerjee, S. C. (1985). *Spontaneous combustion of coal and mine fires*. Oxford & IBH.

Bakhman, N. N. (1992). Smoldering wave propagation mechanism in critical conditions. *Combustion, Explosion and Shock Waves, 29*, 14–17.

Beamish, B. B., Barakat, M. A., & St George, J. D. (2000). Adiabatic testing procedures for determining the self-heating propensity of coal and sample ageing effects. *Thermochimica Acta, 362*, 79–87.

Beamish, B. B., & Hamilton, G. R. (2005). Effect of moisture content on the R70 self-heating rate of Callide coal. *International Journal of Coal Geology, 64*, 133–138.

Bjorkman, J., & Keski-Rahkonen, O. (1992). *Test method for self-ignition of materials* (VTT Publications No. 96). Technical Research Centre of Finland.

Chamberlain, E. A. C. (1974). Spontaneous combustion of coal. *Colliery Guardian, 222*(3), 79.

Clemens, A. H., & Matheson, T. W. (1996). The role of moisture in the self-heating of low-rank coals. *Fuel, 75*(7), 891–895.

Drysdale, D. (1986). Spontaneous ignition within solids and smouldering combustion. In *An introduction to fire dynamics* (pp. 253–277). John Wiley & Sons.

Germain, P., Nguyen, Q. S., & Suquet, P. (1983). Continuum thermodynamics. *Journal of Applied Mechanics, 50*, 1111–1120.

Humphreys, D. R., & Richmond, A. (1987). *Mining and ventilation practice in coal mines liable to spontaneous combustion*. Queensland Department of Mines.

NT FIRE 045. (1992). *Solid materials: Spontaneous ignition temperature by continuous heating*.

Ohlemiller, T. J., & Lucca, D. A. (1983). An experimental comparison of forward and reverse smoulder propagation in permeable fuel beds. *Combustion and Flame, 54*, 131–147.

Smith, A. C., & Lazzara, C. P. (1987). *Spontaneous combustion studies of U.S. coals* (Report of Investigations No. 9079). United States Bureau of Mines.

Sondreal, E. A., & Ellman, R. C. (1974). *Laboratory determination of factors affecting storage of North Dakota lignite* (Report of Investigations No. 7887). United States Bureau of Mines.

Vance, W. E., Chen, X. D., & Scott, S. C. (1996). The rate of temperature rise of a sub-bituminous coal during spontaneous combustion in an adiabatic device: The effect of moisture content and drying methods. *Combustion and Flame, 106*, 261–270.

Van Wingerden, K., & Alfert, F. (1994). *Detection and suppression of smouldering fires in industrial plants: A literature review* (Report No. CMR-94-F25068). Christian Michelsen Research AS.

Vuorio, M., & Weckman, H. (1980). *Measurements of the self-ignition of peat* (Report No. 20). Technical Research Centre of Finland.

Walters, A. D. (1996). Joseph Conrad and the spontaneous combustion of coal: Part 1. *Coal Preparation, 17,* 147–165.

ASTM International. (2004). *Standard classification of coals by rank* (ASTM D388–99). ASTM International.

VTT Research Report. (1996). *Suppressing fires in silos with liquid nitrogen* (Report No. RTE 11313/96).