Behaviour of low rank high moisture coal in small stockpile under controlled ambient conditions-A statistical approach

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Abstract: The low rank high moisture coal have a great tendency to drain out moisture from their pores under suitable ambient atmospheric conditions. The influence of rain has a negative impact which needs to be protected all round. Stage processing of coal with time gap confirms an enhanced rate of moisture loss in low rank coal. Use of multivariate analysis has given a good insight to understand inter-relation of coal properties, specially the control of moisture with time.

Key Words: Low rank Coal, Stockpile, Total Moisture, Equilibrium moisture, ambient drying, XRD, FTIR, DTA, SEM, Factor Analysis, Cluster Analysis

I. Introduction

Low rank coals have high total moisture contents in the range of 30-70wt%. Due to such a high moisture content of the coal, moisture removal is the first and essential step in almost any process for upgrading or utilizing them. Since the moisture removal is known to have a significant effect on the physical and chemical properties of dried coal, understanding of moisture removal is important. A number of studies have been carried out on the drying behavior of coals from a fundamental viewpoint. Moisture, which can be removed by heating the coal up to a temperature of 100°C, may be retained in various forms: 1. as a film, on the surface of each coal particle, and in the interstices between particles, retained by capillary forces. 2. Or “occluded” inside the coal particles. This occluded moisture may be either free moisture (as in a sponge), or hygroscopic moisture which varies with atmospheric conditions, (also called “regain”). These latter forms of moisture are particularly common in “young” coals (subbituminous and lignite).

With the demand of coal by the power sector, the use of low rank coal (LRC) becomes inevitable. This has forced the consumers to look for high moisture thermal coal. Also to improve the efficiency many research work progressed to dry the coal. Below is the outline of few coal drying methods being adopted by power plant or at advanced stage by research of different institutes as explained below.

1. MTE –the mechanical-thermal procedure [1,2]
2. Convective drying in rotational dryers [3-5]
3. Drying followed by briquetting – [6-9]
5. Thermal drying
   1. vibrating fluid bed dryers:: [14,15]
   2. fluid bed dryers:: [16-18]
   3. dryers with in-bed heat exchangers; [19]
   5. Pulsed Combustion Drying [21]
6. Microwave Drying [22-24]
7. Chemical drying [25-26]
8. Fluidised Bed drying – [27]
9. Coal drying in bubbling fluidized beds [28-33]
10. Hydrothermal Dewatering: [34-38]
11. CWS Process [39-42]
12. Integrated drying gasification Process [43-45]
13. The Limax™ Coal Drying System [46]
14. WCT, Australia – Binderless briquetting[47]
15. High velocity air flow grinding/drying - DevourX mill : DXCoal Pty Ltd Australia, LF Pumping Ltd, England

For the high moisture low rank thermal coal of East Kalimantan, Indonesia (current work in TOP Mine Coal in...
Muaraawahau region), all the above options were carefully examined. It was found all these processes have inherent shortcomings considering its applicability due to-

1. Most of the processes are designed and adopted in power plants in situ utilisation
2. No uniform applicability to all types of coal
3. Capacity limitations of each process
4. High Power and capex requirement etc.
5. Space constraint in mining operations because of larger plant foot print
6. Adaptability to very lager volumes or production
7. Limited applicability to Indonesian coals
8. Readsoption of moisture
9. Uneconomical due to Indonesian thermal coal selling price

It is very clear that the moisture present in coal as chemically bound is not easy to remove unless sufficient energy is induced externally; however other types of moistures are easy to remove. A comprehensive overview on the fundamental understanding of water in brown coal and lignite, including the physical and chemical structure of coal, the forms of water present in low rank coals, migration of water during drying, coal structure changes during moisture loss, moisture re-adsorption, and effects of water removal on subsequent applications including combustion, gasification and liquefaction has been reported. [48].

Allardice [49] reported the relationship between water content and heat of desorption for brown coal sample as-

- About 20% of the water is bound more strongly to the coal than the water molecules are to each other.
- For 80% of the water, the heat of desorption is simply the latent heat of evaporation. For the remaining 20%, it is assumed that hydrogen bonding has occurred. This tends to happen within the fine pore structure.
- In the course of drying, the varying strength of the water bond will produce different evaporation behaviour.
- Lignite and some LRC differ significantly from bituminous coal where most of the moisture is present on the surface and loosely bound. In lignite and LRC, a high proportion of the water is held in the pores.

The natural drying would be more suitable and economic choice for taking care of 80% of total moisture which is available in surface with large pore structure, so experiment was aiming to the moisture which are physically bound in nature or freely adhered to coal as loosely bound coal-water matrix. A testing and sampling regime was established, with a degree of confidence, the potential moisture loss via natural drainage and drying of a large sample mined and crushed on the site. The methodology is based on evaluating results from four levels of testing to facilitate the scale up to full production.

II. Experimental

Laboratory scale analysis of coal properties like –Total Moisture (TM), Proximate, Calorific Value, Ultimate, Petrographic, Ash Analysis, Ash Fusion Temperatures, Moisture Holding Capacity (EQM equilibrium moisture), Bulk Density, Relative Density, drop shatter test, and Spontaneous Combustion propensity, XRD, DTA/TG, FTIR, and SEM etc. has been carried out.

The small scale tests were conducted to investigate the potential to drain moisture. The tests show a consistent drainage profile for all tests, This has allowed a defined drainage relationship as discussed below. As these tests were conducted in the ideal conditions of no stockpile segregation, maximum gravity effect and shelter from rain re-wetting, they give indication of the maximum potential for moisture reduction via natural drainage. The results from the small scale drying tests indicate a strong potential to significantly reduce the “as mined” moisture content of coal. All tests showed consistent losses over time with an average weight loss of 27% for the 24 days test period. These test show the maximum possible natural drying potential with no impediments to drainage and no additional moisture load from rainfall. But the test results of large stockpile under ambient conditions had shown that rainfall have got very high detrimental effect on coal dehydration process [50].

Small stockpile natural drying tests –using different granulometry with sheltered and unsheltered conditions in addition of aging process to establish the natural drying optimization with staging process of storage and crushing. In continuation to understand the behaviour of coal moisture loss in ambient conditions, the present work covers in small stockpiles of coal (test plan shown in Table 1).

<table>
<thead>
<tr>
<th>Test Days</th>
<th>0</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>17</th>
<th>20</th>
<th>23</th>
<th>26</th>
<th>29</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM Sample under shelter Pile No</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>ROM Sample without shelter pile No</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
</tbody>
</table>
-100 mm Crushed sample under shelter | 25 | 26 | 27 | 28 | 29 | 30

-100mm Crushed sample without shelter | 31 | 32 | 33 | 34 | 35 | 36

-50 mm Crushed sample under shelter | 37 | 38 | 39 | 40 | 41 | 42

-50mm Crushed sample without shelter | 43 | 44 | 45 | 46 | 47 | 48

- with different granulometry (ROM- Run of Mines, top size 100mm and top size 50mm),
- Under shelter and without shelter
- We have added staging crushing
  - ROM will be stockpiled and monitored for TM and EQM
  - when it was found that TM has come to EQM level of 35% in ROM, the next sample was confirmed for the same level of TM, then ROM will be crushed to <100mm and continue the experiment
  - Further <100mm will be crushed after a time gap to <50mm when TM of -100mm reaches~30% and will be monitored further.
- All samples were tested (ASTM Method) for TM, Proximate analysis, Ultimate Analysis and equilibrium moisture and screened for granulometry change (drop shatter test), HGI.

### 3.1 X-ray Diffraction pattern shows a

3.1 X-ray Diffraction pattern shows a strong base line shifting due to amorphous nature of TOP Coal (Figure 1). This is possibly due to the early stages of coalification process [51], where the wood tissues have not broken due to aging process or not undergone compaction due to overburden to make ordered packing of macromolecules [52] as seen in bituminous coal. Amorphous nature of coal will carry more surface moisture in pore spaces than any occluded moisture. Due to less compaction, the original pore structure of vegetation remains as interconnected.

### 3.2 Combustion behavior of the sample was studied with the help of Simultaneous Thermal Analyzer, model STA 409 C (NETZSCH, Germany) having DSC/TG sample carrier device. Accurately weighed samples (in the range of 20 ± 1 mg) were loaded in an Al₂O₃ crucible of a simultaneous Thermal Analyzer. The experimental run was performed with air flow rate 50 ml/ min and rate of heating was maintained at 10 C/ min.

Four key characteristics of the DTG curve are used when analyzing a burning profile (as shown in Figure 2).

(a) The ignition temperature (IT) is the temperature at which pyrolysis is initiated has been found as 250.7 C. The ignition temperature increases with decreasing volatile matter of coal [53]. The ignition temperature is assumed to be the average temperature in the last time interval where both on pyrolysis and combustion curves coincide [54].

(b) The fixed carbon initiation temperature (ITFC), which may be defined as the temperature at the initial phase of combustion where the rate of weight loss reaches 1.0%/ min, cannot be isolated precisely but estimated as 338.1 C. The IT region and the ITFC region overlap because releasing volatiles from the coal sample creates conditions encouraging combustion.

(c) The peak maximum temperature (PT) is simply the temperature at the peak of the DTG curve noting the
temperature at which maximum weight loss occurs found to be 349.9 to 393.6°C.

(d) The burnout temperature (BT) is the temperature at which the weight loss has ended and a baseline weight has once again been reached was 424.6°C (BT = Temperature ‘C at which loss rate reduces to 1.0%/min at the terminal phase of combustion process).

The TGA curve shows a loss of 11% by weight at a temperature of around 200°C is mostly the surface moisture. DTA results of combustion which allows evaluating about the type of ignition. Flatter curves indicate homogeneous combustion, while sharp peaks are indicative of heterogeneous combustion [55]. The TOP coal shows a very flatter peak in the exothermic event, indicating a predominant homogeneous combustion.

3.3 Fourier transform infrared (FTIR) spectroscopy is a widely used analytical technique for determining the different functional groups of a coal structure. Due to the structural complexity of coal, some studies on FTIR [56] have done assignments of particular bands to various functional groups. Analysis of FTIR spectra in absorbance mode for low rank coal sample reveal some dominant absorbance peaks at certain wave numbers (Figure 3). All assignments were made according to Mayo, Muller & Hannah [57] and the FTIR peaks have been characterized as below-

- Absorbance bands within 3600 cm\(^{-1}\) to 3800 cm\(^{-1}\) are mainly due to OH groups present in clay minerals.
- 3400 cm\(^{-1}\) and 3600 cm\(^{-1}\) are assigned as hydrogen bonded -OH stretching and N－H stretching.
- A weak sharp absorption band at contain a small amount of carboxylic groups at 3733 cm\(^{-1}\).
- The zone of 2800 cm\(^{-1}\) to 3100 cm\(^{-1}\) is significant for aliphatic stretching. The FTIR spectra of most coals show several resolved bands between 2800 and 3000 cm\(^{-1}\) and a well-resolved band between 3000 and 3100 cm\(^{-1}\). The former are assigned to the aliphatic C-H stretching modes of methyl or methylene groups, and the latter is assigned to the aromatic C-H stretching mode [58].

- From 2750 to 3000 cm\(^{-1}\) the bands are attributed to CH\(_3\) and CH\(_2\) (aliphatic), and after 3000 cm\(^{-1}\) the bands are attributed to CH aromatics. The bands near 2921 cm\(^{-1}\) and 2850 cm\(^{-1}\) are assigned to asymmetric and symmetric stretching of sp\(^3\)-CH\(_3\) groups implying presence of long aliphatic chains associated with the coal structures. The bands at 2853, 2870 and 2890 cm\(^{-1}\) have been assigned to the aliphatic C-H symmetric stretching of methylene, methyl and tertiary CH groups respectively. The band at 2830 cm\(^{-1}\) has been assigned to the C-H stretching frequency of the methoxy group [59]. The sharp peaks of FTIR spectra in the region 2855-2921 cm\(^{-1}\) wave length region suggest the coal is immature. With the progress of coalification process the peaks will shift to a lower region.

- Absorbance peak near 1700 cm\(^{-1}\) is indicative of carboxylic acids and Ketone groups while –COO-1 groups are described by the peak near 1610 cm\(^{-1}\). This zone of oxygen-containing functional groups is characterized by a very intense peak at 1618–1622 cm\(^{-1}\), which is attributed either to C=O or C=C aromatic ring stretching. The C=C bands, which should be placed between C=O and C=O bands, were not definitely distinguished, since low rank coals have high oxygen content and these bands almost masked the C=C structures [60]. Band at or near 1650cm\(^{-1}\) denotes conjugated Ketonic structures (Quinones).

- The C=C groups and the C=O groups are recognizable at 1550 cm\(^{-1}\). Presence of 1440 cm\(^{-1}\) bands indicate, in general, the CH\(_2\) groups in bridges, but the same wave number may also indicate the presence of aromatic C=C and bending mode of H-bonded O-H groups. The bands at 1541 cm\(^{-1}\) and 1442 cm\(^{-1}\) is normally present in immature coals with more lignin content [61].

- The band near 1260 cm\(^{-1}\), which is very common in low rank coal, is assigned to ary lethrer structure.

- At the 1200–1000 cm\(^{-1}\) region, a sharp, intensive peak is common for low rank coals. The 1032–1047 cm\(^{-1}\) may also result from silicate minerals (Si–O bonds) from Kaolinite and Illite [62].

- Si–O–Si stretching vibration is represented by the absorbance bands within 1100 cm\(^{-1}\) to 400 cm\(^{-1}\). Presence of quartz and other clay minerals may be responsible for these bands.

- C=O stretching, O-H band in phenox structure, aliphatic ethers and alcohols are responsible for the absorbance bands within 1000 cm\(^{-1}\) to 1300 cm\(^{-1}\) zone.

- Amorphous carbon bands: moderate absorption at 1540 and 1465 cm\(^{-1}\) bands could represent aromatic ring systems typically found in amorphous carbon materials. The band at 1355 cm\(^{-1}\) to benzene or condensed benzene rings in amorphous carbon. The band at 1180 cm-1 to sp3- rich structures in amorphous carbon.
With enhancement in coalfication process, the content of oxygen as COOH decreases and that as OH increases [63]. The comparison of peat and lignite analysis reveals a degradation of methoxy groups, carbohydrates and carboxylic groups during early coalfication, whereas the aliphatic carbons were less affected [64]. The above spectral analyses point to the presence of dominant functional groups associated within coalf structure of lower rank coals.

3.4 From the proximate and ultimate analysis results (Table 2), TOP coal was found to be low rank high with moisture and very low sulphur & low ash content, which is typical of Muarawahau formation in East Kalimantan, Indonesia. The sample found to have an equilibrium moisture content of 34.2%adb. Hardgrove index (HGI) of the sample was 61 was considerably harder although very young coal. The relative ignition temperature was found to be 132 °C is also quite high for propensity to self-combust.

### Table 2: Chemical analysis of coal samples (air dried basis)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Moisture</td>
<td>%arb</td>
<td>47.42</td>
</tr>
<tr>
<td>Moisture in Analysis Sample</td>
<td>%adb</td>
<td>15.12</td>
</tr>
<tr>
<td>Ash Content</td>
<td>%adb</td>
<td>1.96</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>%adb</td>
<td>42.81</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>%adb</td>
<td>40.12</td>
</tr>
<tr>
<td>Total Sulfur</td>
<td>%adb</td>
<td>0.13</td>
</tr>
<tr>
<td>Calorific Value (adb)</td>
<td>Kcal/kg</td>
<td>5583</td>
</tr>
<tr>
<td>Carbon</td>
<td>%adb</td>
<td>42.72</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>%adb</td>
<td>2.64</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>%adb</td>
<td>0.80</td>
</tr>
<tr>
<td>Oxygen</td>
<td>%adb</td>
<td>13.21</td>
</tr>
<tr>
<td>HGI - Hard Groove Index</td>
<td>Index</td>
<td>61</td>
</tr>
<tr>
<td>Moisture Holding Capacity %</td>
<td>%adb</td>
<td>34.2</td>
</tr>
<tr>
<td>Relative Ignition Temperature</td>
<td>°C</td>
<td>132</td>
</tr>
</tbody>
</table>

3.5 In the younger coals like TOP Coal, the coalfication process has not advanced so far, and a substantial amount of water is present in the pore structure (SEM Photo, Figure 4) Although the overall porosity of TOP Coal is similar to bituminous coal, about 0.1ml/g, there are larger interconnected pores of over 5 mm diameter in TOP Coal. A larger proportion of the porosity is accounted for in the larger diameter interconnected pores, and in turn these hold a large fraction of the total moisture content. The macro-pore system in coals is strongly influenced by overburden pressure. By contrast, the micro-pore structure depends on the chemical make-up of the coal and is largely dependent of the confining stress during the formation stage The drying rate increased with air velocity. Thus, the larger drying rates associated with the larger particles, are due to higher air velocities and not to any inherently higher rates of drying due to particle size. This suggests that, in this particle size range, drying rate is controlled by the internal pore structure of the coal.

3.6 The ash chemistry (table 3) found to have enrichment of Fe₂O₃, apart from SiO₂ and Al₂O₃ as major constituent. From the XRD, we have detected Goethite in few samples which are carrier of iron in ash. Although the iron content seems high in ash but considering the low ash % in coal, contribution of iron in total coal will be very low.

### Table 3: Ash chemistry and fusion temperature

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon as SiO₂</td>
<td>%adb</td>
<td>46.00</td>
</tr>
<tr>
<td>Aluminum as Al₂O₃</td>
<td>%adb</td>
<td>20.30</td>
</tr>
<tr>
<td>Iron as Fe₂O₃</td>
<td>%adb</td>
<td>17.45</td>
</tr>
<tr>
<td>Calcium as CaO</td>
<td>%adb</td>
<td>5.60</td>
</tr>
</tbody>
</table>
The characteristic melting temperatures are related to the transformations and reactions of ash and these are interpreted in terms of their importance to fouling and slagging in furnaces. Ash fusion temperatures typically are measured at four defined points under both reducing and oxidizing conditions. Generally, a temperature under reducing conditions should be equal to or lower than the corresponding temperature under oxidizing conditions. The difference in these temperatures generally increases with increasing iron content in the ash. The initial deformation temperature of 1240 °C with flow temperature of 1340 °C in oxidizing and 1330 °C in reducing atmosphere is considerably accepted as a suitable blend for boiler operations.

IV. Statistical data analysis

The data generated in the experiment having 50 variables and 45 data columns for this study. To analyze such huge data with so many variables, first we tried to use a simple linear correlation method. With this we could able to reestablish the same understanding what we had earlier between the variables. It was very difficult to understand the inter-relationship among the variables taking all at a time. This has demanded us to use multivariate approach. For this we have selected Cluster analysis and Factor analysis package and the software used was Minitab version 17.

A. Factor analysis

Factor analysis generates a table in which the rows are the observed raw indicator variables and the columns are the factors or latent variables that explain as much of the variance in these variables as possible. The cells in this table are factor loadings, and the meaning of the factors must be induced from seeing which variables are most heavily loaded on which factors. These techniques are commonly used when developing a questionnaire to see the relationship between the items in the questionnaire and underlying dimensions. It is also used in general to reduce a larger set of variables to a smaller set of variables that explain the important dimensions of variability. There are several different types of factor analysis, with the most common being principal components analysis (PCA), R-mode factor analysis. R-mode is by far the most common. In R-mode, rows are cases, columns are variables, and cell entries are scores of the cases on the variables. In R-mode, the factors are clusters of variables on a set of other entities, at a given point of time. Rotation serves to make the output more understandable, and is usually necessary to facilitate the interpretation of factors. Factors are rotated according to various possible criteria, with the object of making the factors each relatively independent of the independent variables, consistent with the other objectives. The sum of Eigen values is not affected by rotation, but rotation will alter the Eigen values of particular factors and will change the factor loadings. Varimax rotation is an orthogonal rotation of the factor axes to maximize the variance of the squared loadings of a factor (column) on all the variables (rows) in a factor matrix, which has the effect of differentiating the original variables by extracted factor. That is, it minimizes the number of variables that have high loadings on any one given factor. Each factor will tend to have either large or small loadings of particular variables on it. A Varimax solution yields results that make it as easy as possible to identify each variable with a single factor. The results are summarized in Table 4; factoring loading values below ±0.40 are ignored considering their low influence.
A.1 Factor 1: Constitutes all the original chemical components of coal. Total moisture: all of the moisture in and on a sample of coal; commonly determined quantitatively by air drying a sample and then assaying residual moisture in the air-dried sample; thus, total moisture is the sum of the air-dry loss and the residual moisture adjusted to an as-received basis (ASTM D-2961; ASTM D-3302). Both air dry loss (ADL) and Total Moisture (TM) are negatively correlated to all other components of coal which is a natural phenomenon of coalification. The association of ADL and TM under one factor clearly confirms the major influence and contribution of ADL towards the total moisture of coal. Residual moisture: moisture remaining in the sample after air drying; assayed by determining the mass lost from drying the sample at 104 to 110°C (219 to 230°F) at specified conditions of residence time, atmosphere, particle size, sample mass, and equipment configuration (ASTM D-3173; ASTM D-3302). The residual moisture in not covered under this factor is quite surprising. This means residual moisture is of different category possibly of different nature than the other moisture available in coal. The residual moisture is that moisture that is still locked up in the coal after air-drying. The higher ranked coals that ASTM standards were based on possess this well-defined split between the air-dried or surface moisture and the residual or near EQ moisture. This is not the case for low rank coals. The sponge-like or wood like nature of low rank coal make the split between surface moisture and inherent moisture a rather fuzzy line [65]. Total sulphur to be part of this factor indicates the source of the sulphur in this type of coal is organic, which is from plant debris not mineral matter constituents from ash of coal. From the X-ray diffractograms also we have not observed any sulphur bearing minerals presence confirms this observation.

Table 4 showing results of Factor Analysis

<table>
<thead>
<tr>
<th>Variables</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days</td>
<td>F1 0.68</td>
</tr>
<tr>
<td>ADL, %ar</td>
<td>F2 -0.45</td>
</tr>
<tr>
<td>Residual Moisture, %adb</td>
<td>F3 -0.92</td>
</tr>
<tr>
<td>Total Moisture, %ar</td>
<td>F4 -0.52</td>
</tr>
<tr>
<td>EQM, %ar</td>
<td>F5 -0.73</td>
</tr>
<tr>
<td>Moisture in Sample, %adb</td>
<td></td>
</tr>
<tr>
<td>Ash, %adb</td>
<td>F1 -0.61</td>
</tr>
<tr>
<td>VM, %adb</td>
<td>F2 0.61</td>
</tr>
<tr>
<td>FC, %adb</td>
<td>F3 0.67</td>
</tr>
<tr>
<td>TS, %adb</td>
<td>F4 0.80</td>
</tr>
<tr>
<td>CV, Kcal/kg adb</td>
<td>F5 0.88</td>
</tr>
<tr>
<td>CV, Kcal/kg daf</td>
<td></td>
</tr>
<tr>
<td>HGI</td>
<td>F1 -0.75</td>
</tr>
<tr>
<td>Carbon, %daf</td>
<td>F2 0.77</td>
</tr>
<tr>
<td>Hydrogen, %daf</td>
<td>F3 0.46</td>
</tr>
<tr>
<td>Nitrogen, %daf</td>
<td>F4 0.87</td>
</tr>
<tr>
<td>TS, %daf</td>
<td>F5 0.75</td>
</tr>
<tr>
<td>Diff. + 50 mm</td>
<td></td>
</tr>
<tr>
<td>Diff. -50 + 31.5</td>
<td>F1 0.65</td>
</tr>
<tr>
<td>Diff. -31.5 + 22.4</td>
<td>F2 0.73</td>
</tr>
<tr>
<td>Diff. -22.4 + 16</td>
<td>F3 0.56</td>
</tr>
<tr>
<td>Diff. -16 + 11.2</td>
<td>F4 0.79</td>
</tr>
<tr>
<td>Diff. -11.2 + 8</td>
<td>F5 0.61</td>
</tr>
<tr>
<td>Diff. -8+4</td>
<td>F1 0.56</td>
</tr>
<tr>
<td>Diff. -4+2</td>
<td>F2 -0.65</td>
</tr>
<tr>
<td>Diff. -2+1</td>
<td>F3 -0.90</td>
</tr>
<tr>
<td>Diff. -1+0.5</td>
<td>F4 -0.88</td>
</tr>
<tr>
<td>Diff. -0.5</td>
<td>F5 -0.77</td>
</tr>
<tr>
<td>% Variance</td>
<td>F1 20.1</td>
</tr>
<tr>
<td></td>
<td>F2 16.5</td>
</tr>
<tr>
<td></td>
<td>F3 15.9</td>
</tr>
<tr>
<td></td>
<td>F4 10.9</td>
</tr>
<tr>
<td></td>
<td>F5 9.0</td>
</tr>
<tr>
<td>Total Variance</td>
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</tbody>
</table>

A.2 Factor 2: This is very important observation. The number of days (ambient condition drying time) is correlated negatively with the equilibrium moisture (EQM). This means, EQM will drop with increased exposure time. Also EQM is positively correlated with +50mm fraction and all other fractions have negative correlation with the EQM. This has given a good indication that major contributor of EQM is +50mm fraction. In other words suitable granulometry change with time can be optimized to have a better control of EQM. Decrepitation to smaller grain sizes of the coal with time (Figure 5), that the smaller the grain sizes the larger the surface area and the more contact with oxygen, and heat was continuously accumulated in the medium and could not be taken out [66], helps in lowering of equilibrium moisture further. The rewetting of partly dry coal regarded as a more serious trigger for the production of heat with time. Laboratory measurements have shown that such heats of wetting can range as high as 85 to 105 J/g, sufficient to raise the oxidation temperature of the coal by 25 to 30°C and increase oxidation rates six- to eight-fold [67]. Wetting of coal takes place when stockpiled coal is exposed to rain after a period of dry, sunny weather, or when wet coal is placed on a dry pile. Porosity and Equilibrium moisture of coal are closely interrelated [68] and low rank coals with larger pores may
experience evaporation from pores at high humidity [69]. It is shown that larger particle sizes give rise to a higher drying rate. The loss of EQM will help the low rank coal to reduce the propensity of self-ignition. Generally when the moisture content of low rank coal decreases by 1%, the coal calorific value will increase by 88 kcal/kg, [70] improving the techno-economic suitability.

Figure 5: Ambient condition decrepitation of coal granule with loss on surface moisture
A-47% TM, B-38% TM and C-34% TM and shrinkage in volume

A.3 Factor 3: Residual moisture is separated out in this factor. May be the pore distribution and macerals & inorganic constituent’s chemistry plays a role in the residual moisture content of coal. Hydrogen found to have negative correlation with residual moisture. The H concentrations increase with increasing of residual moisture, hydrated minerals, and methane in coals [71]. However, we have observed an opposite relation. The increased contents of H are normally more characteristic of lower-rank coals. Volatile matter does not contain the moisture of coal but it contains water that is formed from the hydrogen and oxygen of coal during the decomposition. Free water may exist in the coal as adsorbed on the surface, condensed inside fine capillary network and as bound to the coal molecule by chemisorption and hydrogen bonding. Water molecules bond to the coal on oxygen functional groups (OH and COOH) using oxygen in the coal and hydrogen bonds in the water molecules [72] was also considered. The possibility is that part of the hydrogen was a byproduct of the oxidation of the coal and has negative correlation with residual moisture.

A.4 Factor 4: All the weathered components of the granulometry below 4 mm have been grouped together because of their common origin, oxidation followed by decrepitation of coal. They have no influence on the TM as the nature of moisture available in the decrepitated product may be of different nature due to weathering and partial oxidation. Low-rank coals can lose 25 to 30 percent of their original mass during air drying [67]. During ambient drying, desorption of moisture from external surface of coal will always be faster than desorption from its inner layer. Such de-hydration is accompanied by extensive, partially irreversible volume shrinkage, and the internal stresses set up quickly cause the coal to lose its cohesion and to disintegrate into progressively smaller pieces. This disintegration is known as decrepitation or slaking, which results in more surface area of coal. Depending on the humidity of atmosphere the coal will continue to adsorb and desorb moisture and these disintegrated fractions play a major role in this process. These products of decrepitation have changed pore structure and moisture contents than the original mass and have distinctly different behaviour [73], which are indicted from their separate grouping into one factor.

A.5 Factor 5: Ash in coal found to be influencing the TM of coal. As the ADL component is also correlated with ash, this indicates the ash is carrying moisture external contamination not inherent with coal may be natural weathering as the sample was in the out crop area of the seam. Also we have seen HGI of coal is influenced by ash as well as TM of coal. As the TM increases the HGI values also goes up indicating coal is softer. The Hardgrove Grindability index value is influenced by petrographic composition of coal. The analysis of grindability of British coal confirmed wide relation of HGI values between the quality group of coal, volatile combustible matter contents, carbon and hydrogen [74]. The increase of contents of volatile combustible matter improves the grindability up to the contents of volatile combustible matter of approximately 30%, beyond which the grindability deteriorates. Similarly the HGI value increases with the growth of carbon contents. The grindability then drops rapidly with the contents of carbon exceeding approximately 92% that is inherent moisture decreases with increasing coal rank. It was found that as the inherent moisture in coal increased the HGI values also increased [75]. The grindability is significantly influenced also by the contents of ash in coal [76, 77] and found to correlate well with residual moisture [78].

B. Cluster analysis
The underlying and basic difficulty, of course, is that factor analysis has no way of distinguishing between “true correlations” and “error correlation” reported the empirically greater usefulness of cluster analysis rather than factor analysis. Cluster analysis identifies and classifies object individuals or variables on the basis of the similarity of the characteristics they possess. It seeks to minimize within-group variance and maximize between-group variance. The result of cluster analysis is a number of heterogeneous groups with homogeneous contents. There are substantial differences between the groups, but the individuals within a single group are similar. Each cluster thus describes, in terms of the data collected, the class to which its members belong; and this description may be abstracted through use from the particular to the general class or type. The term cluster analysis actually
encompasses a number of different classification algorithms, which organize observed data into meaningful structure. In general, whenever one needs to classify a "mountain" of information into manageable and meaningful piles, cluster analysis is of great utility. The result of cluster analysis is shown in figure 6. There are four major clusters of variables could be seen

- **Cluster 1**: following Carbon, Total Moisture is major one
- **Cluster 2A**: Number of days and residual moisture
- **Cluster 2B**: Calorific Value, daf
- **Cluster 2C**: Ash
- **Cluster 3A1**: VM and TS
- **Cluster 3A2**: FC and TS daf
- **Cluster 3B**: CV adb
- **Cluster 3C**: HGI
- **Cluster 3D**: H
- **Cluster 3E**: Moisture in sample by TGA
- **Cluster 4A**: Air dried loss (ADL)
- **Cluster 4B**: Equilibrium moisture EQM
- **Cluster 4C**: Granulometry

Cluster analysis clearly separated total moisture as the major variable amongst the 50 variables considered in the study. The three dimensions of control of total moisture can be understood by the three cluster dendograms shown in figure 6. From the cluster 2 it can be seen that number of days and residual moisture has shared in one cluster. This means exposure time affects the residual moisture content and ultimately the TM. To some extent it was seen that ash is also playing a role in residual moisture content of the coal. The moisture in sample is present in Cluster 3 comprises of all the test results of TGA, so they are grouped together. Cluster 4 components are very important to understand. Both ADL and EQM in one side and all the granulometry fractions on the other side of the cluster. This indicates very clearly that both ADL and EQM is a function of the granulometry a product of oxidation. This is very important observation to apply in the field at different process levels in order to achieve the required ADL and EQM which in turn is reflecting the TM in coal and ultimately the calorific value of coal.

![Figure 6: Cluster Analysis Dendograms](image)

**V. Conclusion**

It is evident from the available literatures that processing or upgrading technologies for low rank high moisture coals at the power plant end may be a suitable solution but at the mine may not be technically feasible due to many techno-commercial limitations. Best way is to utilize the natural climatic conditions in a controlled manner. Because the low rank high moisture coals carry majority of their moisture in surface and inside the pore structure, good dry weather helps in lowering of total moisture. In summary, TOP coal with average 47% TM with 30-35% ADL which is surface moisture, a significant part of this moisture gets evaporated in ambient atmospheric conditions under shelter, with proper staging and suitable sizing methods. The TOP Coal reaches to equilibrium stage of 27% TM in small scale test. However, optimization of the TM content could be achieved to 35-40% in large scale tests. Stage processing under controlled ambient condition of low rank coal stockpile results in boosted lowering in moisture and enhancement in calorific value. Both Factor analysis and Cluster
analysis has given a very good insight on the inter-correlation of various chemical and physical parameters of low rank coal.

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