**Table 1** Classification of hardness measurement method

|  |  |  |  |
| --- | --- | --- | --- |
| Classification | Name | Measurement method | Indication of hardness |
| Pressing | Rockwell | Press the specimen with a diamond cone or steel ball with a radius of 0.2mm and a vertex angle of 120° | Difference in depth when two types of load are applied |
| Vickers | Press the specimen with a four-angle diamond with a face-to-face angle of 136° | Average pressure per surface area pressed |
| Brinell | Press the specimen with a steel ball (1, 2, 2.5, 5, 10mm) | Average pressure per surface area pressed |
| Knoop | Press the specimen with a diamond square pendulum of 172° 30’ and 130° | Average pressure per surface area pressed |
| Durometer | Press the specimen with a spherical or conical needle | Depth of press at constant load |
| Barcol | Press the specimen with a conical needle | Depth of press at constant load |
| Dynamic | Shore | Drop the hammer with the diamond tip on the specimen | Height of bouncing |
| Equotip | Hit the specimen with a manner with a permanent magnet attached | Ratio between collision speed and rebound speed |
| Thickness | Mohs | Scratch each other’s specimens and standard minerals | Estimate from the hardness of the standard mineral |
| Meyer | Scratch the specimen with the diamond cone with an angle of 90° on the tip | Average pressure when scratching |
| Martens | Scratch the specimen with the diamond cone with an angle of 90° on the tip | Load required to scratch 0.1mm |
| File | Compare the specimen with the standard specimen in a file | Value between the hardness values of the standard specimen |

**Table 2** Element composition of asphalt

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Elements | Carbon | Hydrogen | Oxygen | Nitrogen | Sulfur | Metal(Fe, Ni, etc.) |
| Composition ratio (wt%) | 80-85 | 9-10 | 2-8 | 0.5-1.0 | 0.5-7.0 | negligible |

**Table 3** Proximate analysis and unburned carbon contents of high carbon ash

|  |  |  |
| --- | --- | --- |
| Sample | Unburned carbon content (wt%) | Proximate analysis (wt%) |
| Moisture | Volatile matter | Ash | Fixed carbon |
| T-P | 19.60 | 25.60 | 3.12 | 66.27 | 5.01 |
| D-F | 5.79 | 0.25 | 2.00 | 95.52 | 2.23 |
| SA-B | 17.43 | 14.78 | 1.56 | 83.55 | 0.11 |
| SA-P | 12.41 | 9.09 | 8.18 | 77.87 | 4.86 |
| S-F | 21.75 | 0.01 | 1.60 | 77.08 | 21.18 |
| S-B | 6.61 | 6.08 | 2.63 | 88.52 | 2.77 |
| S-P | 21.57 | 16.05 | 3.02 | 60.31 | 20.44 |
| Y-F | 24.70 | 0.50 | 2.04 | 74.16 | 23.30 |
| Y-B | 22.62 | 16.82 | 2.10 | 78.15 | 2.93 |
| DO-F | 8.20 | 1.00 | 9.43 | 88.36 | 1.34 |

**Table 4** Ultimate analysis of high carbon ash

|  |  |  |
| --- | --- | --- |
| Sample | Ultimate analysis (wt%) | Heating value(kcal/kg) |
| Carbon | Hydrogen | Nitrogen | Oxygen | Total sulfur | Higher | Lower |
| T-P | 2.58  | 0.22  | 0.26  | 30.50  | 0.17  | N.C. |
| D-F | 0.63  | 0.18  | 0.30  | 3.21  | 0.16  | N.C. |
| SA-B | 0.04  | 0.16  | 0.33  | 15.916  | 0.004  | N.C. |
| SA-P | 13.70  | 0.20  | 0.67  | 7.553  | 0.007  | 780  | 710  |
| S-F | 18.65  | 0.22  | 0.65  | 3.35  | 0.05  | 1,230  | 1,220  |
| S-B | 0.72  | 0.15  | 0.59  | 10.01 | 0.01  | N.C. |
| S-P | 25.10  | 0.23  | 0.66 | 13.63 | 0.07  | 1,340  | 1,230  |
| Y-F | 22.35  | 0.22  | 0.54  | 2.62  | 0.11  | 1,280  | 1,270  |
| Y-B | 4.63  | 0.18  | 0.24  | 0.24  | 0.005  | N.C. |
| DO-F | 0.55  | 0.24  | 0.43  | 0.43  | 0.02  | N.C. |

\* N.C.: Not combustible

**Table 5** Diffusivity, conductivity and specific heat at constant pressure of high carbon ash

|  |  |  |  |
| --- | --- | --- | --- |
| Sample | 　Diffusivity(mm2/s) | Conductivity(W/m·K)　 | Cp(J/g/K) |
| 25℃ | 100℃ | 300℃ | 25℃ | 100℃ | 300℃ | 25℃ | 100℃ | 300℃ |
| Flame | 0.103 | 0.076 | 0.050 | 0.074 | 0.097 | 0.060 | 1.188 | 2.099 | 1.971 |
| Fly ash | D | 0.090 | 0.075 | 0.053 | 0.055 | 0.063 | 0.052 | 0.647 | 0.885 | 1.040 |
| S | 0.101 | 0.059 | 0.066 | 0.067 | 0.072 | 0.066 | 0.694 | 0.855 | 1.073 |
| Y | 0.092 | 0.072 | 0.055 | 0.058 | 0.063 | 0.058 | 0.608 | 0.837 | 1.005 |
| DO | 0.094 | 0.076 | 0.056 | 0.059 | 0.065 | 0.048 | 0.792 | 1.084 | 1.102 |
| Bottom ash | SA | 0.125 | 0.093 | 0.072 | 0.152 | 0.248 | 0.092 | 1.152 | 2.519 | 1.211 |
| S | 0.110 | 0.095 | 0.091 | 0.064 | 0.072 | 0.083 | 0.622 | 0.813 | 0.980 |
| Y | 0.181 | 0.138 | 0.107 | 0.172 | 0.361 | 0.089 | 0.955 | 2.623 | 0.828 |
| Ponded ash | T | 0.120 | 0.076 | 0.061 | 0.168 | 0.272 | 0.051 | 1.552 | 3.977 | 0.927 |
| SA | 0.063 | 0.068 | 0.056 | 0.050 | 0.092 | 0.039 | 0.944 | 1.665 | 0.840 |
| S | 0.118 | 0.081 | 0.069 | 0.151 | 0.197 | 0.043 | 1.397 | 2.673 | 0.683 |

**Table 6** Activation energy and frequency factor for high carbon ash

|  |  |  |  |
| --- | --- | --- | --- |
| Sample name | Activation energy (kJ/mol) | Frequency factor (S-1) | R2 |
| Bituminous | Flame | 18.944  | 91,419  | 0.790 |
| Fly ash | DF | 136.842  | 2,962  | 0.995 |
| SF | 68.442  | 2,962  | 0.998 |
| YF | 104.578  | 105  | 0.998 |
| DOF | 33.945  | 167,920  | 0.928 |
| ave. | 85.952  | 43,487  | - |
| Pond ash | TB | 33.668  | 103,305  | 0.975 |
| SAB | 15.273  | 390,070  | 0.002 |
| SB | 58.582  | 7,638  | 0.997 |
| YB | 24.477  | 263,560  | 0.750 |
| ave. | 38.909  | 124,834  | - |