Flow properties and design procedures for coal storage bins

Brian A. Moore

University of Wollongong

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FLOW PROPERTIES
AND
DESIGN PROCEDURES
FOR COAL STORAGE BINS

A thesis submitted in fulfilment of the
requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

from

THE UNIVERSITY OF WOLLONGONG

by

B. A. MOORE, BE, MIEAust.

Department of Mechanical Engineering
1988
This is to certify that this work has not been submitted for a degree to any other university or institution.

Brian A. Moore
Dedicated to my wife, Cathy, and my daughter, Emma, for their encouragement, support and love.
ABSTRACT

The handling and storage of black coal has always presented industry with problems of erratic or spasmodic feed, partial reclamation of the total contents of bins and flow blockages at hopper outlets. These problems can lead to extreme cost penalties for all users, from the coal producers and export market loading facilities to the secondary industries using coal for process energy requirements. Any reduction in the occurrence of these handling problems and the subsequent increase in efficiency would be of benefit.

The aim of this work was to investigate two major aspects in the design of coal storage bins to ensure reliable and predictable operation, particularly in regard to gravity assisted discharge.

First, an experimental study investigated the flow properties of black coal and the influence on these flow properties of variations in the physical characteristics of the test samples. Variables considered included moisture content, particle top size of test samples, coal particle shape, time consolidation at rest and ash content. Samples for the test program were obtained from the six collieries located in the Southern Coalfields (Illawarra Measures) of the Sydney Basin of New South Wales. The coals ranged in rank from sub-bituminous to semi-anthracite.

The study highlighted the most influential variables to be moisture content, sample particle size and time consolidation at rest. Other factors such as particle shape, coal rank and ash content were minor considerations. Often a variation of variable affected other properties and led to decreased sample flowability. A common example was that of coals with a high friability; this leads to greater particle degradation and generation of fines with handling operations, which then leads to higher
moisture retention capabilities and significantly large critical arching dimensions, particularly with time storage.

The flow property testing program utilised a Jenike-type Direct Shear Tester for the coal sample shear testing. To improve the consistency of this instrument, and eliminate operator and test data interpretation related errors a standardised testing procedure was developed.

The second aspect of investigation dealt with the design procedures for the determination of mass flow hopper geometries based on the coal flow properties and utilising the well accepted theories of Jenike. A novel method of design data presentation was developed which links the flow properties and the hopper geometry parameters. This was achieved by presenting all parameters as a function of a common independent variable, the major consolidation stress. This approach has advantages in accounting for experimental error in the flow properties and for the determination of hopper geometries that have design constraints.

The hopper design procedures were further advanced by the development of an alternate presentation of the original Jenike flow factor charts. These alternative charts have been abbreviated to display only the critical design values in the border region between mass flow and funnel flow. The charts eliminate the need for imprecise parameter interpolations by displaying the required design parameters in the form of contours of constant wall slope and flow factor as a function of the effective angle of internal friction and kinematic angle of wall friction.

These new concepts were combined to allow the generation of manual hopper geometry design nomograms or worksheets. This design presentation represents a compact and rapid method for the determination of mass flow hopper geometry parameters for axisymmetric and plane flow outlets.
The influence and sensitivity of the coal sample variations was explored further by determining the hopper geometry parameters of wall slope and outlet dimension based on the respective flow properties. This has allowed standardised hopper design guidelines to be formulated. An important aspect highlighted by this study was the significant role of wall friction in achieving a successful design.

In consideration of the design procedures for bulk solid storage, computer software was developed and implemented for the computer aided design of storage bins. Two programs were developed, the first, to aid in the rapid processing and analysis of experimental flow property data, describing the flow properties by empirical equations and graphically. The second program utilised the empirical flow property equations for the determination of critical hopper geometry parameters and the generation of other design graphs. The programs operate both on a mainframe computer and a microcomputer, and utilise interactive execution and high resolution graphics.
ACKNOWLEDGEMENTS

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NOMENCLATURE

A : coefficient of the three parameter empirical equation
b : compressibility constant, exponent used to relate bulk density to consolidation stress
: intercept of the linear empirical equation
B : critical arching dimension (width or diameter) for a mass flow hopper
: coefficient of the three parameter empirical equation
B_c : critical arching dimension for an axisymmetric hopper
B_ct : critical arching dimension for an axisymmetric hopper under time storage conditions
B_p : critical arching dimension for a plane flow hopper
B_pt : critical arching dimension for a plane flow hopper under time conditions
C : coefficient of the three parameter empirical equation
c : coefficient of the Warren Spring yield locus equation
D_f : critical piping or ratholing dimension for funnel flow
F : unconfined yield force under instantaneous conditions
ff : flow factor for a converging flow channel
FF : flow function for a bulk solid
FF_t : time flow function
g : acceleration due to gravity
h : depth variable in vertical section
H : height of mass flow cylinder
total height of funnel flow bin
h_f : effective consolidation head of material, funnel flow design
HGI : Hardgrove Grindability Index
H(α) : design function of α and hopper outlet shape [1]
L : length of hopper outlet slot for plane flow hopper
m : hopper outlet shape, axisymmetric (m=1) or plane flow (m=0)
: gradient of the linear empirical equation
n : size distribution parameter from Rosin-Rammler Distribution
: coefficient of the Warren Spring yield locus equation
: number of readings of statistical distribution
R : % weight retained on a sieve aperture, Rosin-Rammler Distribution.

R_a : the arithmetic mean of the profile height deviations of a surface
S : steady state shear force during the "shear consolidation" phase of shear test
S_{selected} : the value of S selected for a particular level of consolidation and used for prorating $\overline{S_i}_{test}$ values.
S_{test} : an uncorrected value of S determined from the shear test
S_i : maximum value of shear force obtained during the "sample shear" phase of the shear test

$\overline{S_i}_{prorated}$ : a corrected value of $S_i$ obtained using the prorating technique

$\overline{S_i}_{test}$ : an uncorrected value of $S_i$ determined from the shear test
T : coefficient of the Warren Spring yield locus equation
V : vertical force due to total vertical load applied at shear plane during the 'shear consolidation' phase of the shear test
V = V_a + V_b
V_a : vertical force due to the mass of the shear lid, shear ring and bulk solid above the shear plane (that is, contained within the shear ring)
V_b : vertical force due to the weight applied to the shear lid during the shear consolidation phase of shear test
V_t : vertical force due to the weight applied to the twisting lid during the pre-consolidation phase of shear test
$V_{b_1}$ : vertical force due to the weight applied to the shear lid during the sample shear phase of shear test

$\overline{V_1}$ : vertical force due to total vertical load applied at shear plane during 'sample shear' test; $\overline{V_1} = V_a + V_{b_1}$

$V_1$ : major consolidating force on sample

$\overline{x}$ : mean value of a distribution

$\chi$ : sieve aperture under consideration, Rosin-Rammler Distribution

$\overline{\chi}$ : size modulus for Rosin-Rammler Distribution

$\alpha$ : half angle of hopper or slope of hopper wall measured from the vertical

$\alpha_c$ : half hopper angle for axisymmetric hopper

$\alpha_{ct}$ : half hopper angle for axisymmetric hopper for time storage conditions

$\alpha_p$ : half hopper angle for a plane flow hopper

$\alpha_{pt}$ : half hopper angle for a plane flow hopper for time storage conditions

$\gamma$ : weight bulk density of a bulk solid

$\delta$ : effective angle of internal friction of a bulk solid

$\phi$ : kinematic angle of wall friction developed between a hopper wall and a bulk solid

$\phi_t$ : static angle of internal friction

$\rho$ : bulk density of a bulk solid

$\rho_o$ : characteristic bulk density value from bulk density variation equation

$\sigma$ : normal stress

$\sigma_o$ : characteristic stress value from the bulk density variation equation

$\sigma_1$ : major consolidation stress

$\overline{\sigma_1}$ : major stress acting at the abutment of a cohesive arch
\( \sigma_c \) : unconfined yield stress of a bulk solid

\( \sigma_{ct} \) : unconfined yield stress of a bulk solid under conditions of time storage at rest

\( \tau \) : shear stress
CHAPTER 1

INTRODUCTION

The quantities of Australian coal, which pass through surge and storage bins annually is considerable and continually increasing. This trend applies not only to the coal producers and export market facilities, but to coal users in such industries as steelmaking, electricity generation and cement manufacture. The achievement of reliable gravity flow is essential, particularly with the increasing size of the storage units and the automation of bulk solid material handling and processing systems.

These trends are exacerbated when from a flow or 'handleability' viewpoint it may be considered that the quality of coal is reducing in present times. This is due to a number of factors, including modern coal mining techniques and increasingly efficient froth flotation techniques in coal preparation plants producing finer coal, and, the acceptance of coal with higher ash contents as being a marketable proposition.

The present state of the art for the design of storage bins for reliable flow and structural integrity require complete flow property tests to be carried out on each new bulk solid considered. With due attention to the bulk solid flow properties, designs often can be achieved that utilise gravity for reliable flow. Within this scenario it would be advantageous if the major physical variables of coal and their influence on the flow properties were to be identified and assessed with a view to reducing the sample testing required and developing standard design rules and rationale.

In the field of bulk solids handling it is essential that both the storage and the discharge from storage of materials is carried out in an effective and efficient manner. However, it is known that flow out of bins
and hoppers is often unreliable and as a result considerable costs can be incurred due to the consequential losses in production. This is very often the case with coal handling plant due to the cohesive and variable nature of coals. Problems that commonly occur in the operation of storage bins (including solids segregation, erratic flow, flooding, arching, piping and adhesion to the bin wall) can reduce the bin capacity below the designed values, or lead to flow blockages. In most cases the problems that occur in practice are due to inadequate design analysis compounded by a lack of knowledge or appreciation of the relevant flow properties of the materials. All too often the design of bins and hoppers for the storage of coal has been treated empirically with little or no regard for the relevant flow properties and the fundamental concepts of the behaviour of bulk solids.

In recent years significant advances have been made in the development of the theories and associated analytical procedures to describe the behaviour of bulk solids under the variety of states that are encountered in materials handling operations. Of particular note is the pioneering work of Dr. A.W. Jenike and his colleague Dr. J.R. Johanson in the formulation of comprehensive mathematical models describing the flow of cohesive bulk solids from bins and hoppers and the required associated design procedures.

The Jenike theory has precipitated a great deal of research throughout the world on problems associated with the storage and flow of bulk solids. As a result there are now well established testing techniques for the measurement of bulk solid strength and flow properties and industrially proven procedures for bin design and evaluation.

For the purpose of providing a suitable background to the investigations covered in this work a brief overview will presented of the philosophy of bin design, the experimental techniques for flow property determination and application of the flow properties to hopper design.
Readers are also referred to References [1 - 4] where the general theories pertaining to the gravity flow of bulk solids in hoppers and the associated design procedures are documented more fully.

1.1 BIN DESIGN PHILOSOPHY

The design of storage bins for bulk solids is basically a four step process:

- Determination of the strength and flow properties of the bulk solids for the worst likely conditions expected to occur in practice.
- Determination of the bin geometry to give the desired capacity, to provide a flow pattern with acceptable characteristics and to ensure that the discharge is reliable and predictable.
- Estimation of loadings exerted on the bin walls and the feeder under operating conditions.
- Design and detailing of the bin structure.

It is important that all bin design problems follow the above procedures. When investigating the required bin geometry, it should be assumed that gravity will provide a reliable flow from storage. Not until it has been demonstrated that the gravity forces available are insufficient to provide reliable flow should more sophisticated reclaim methods or flow aids be investigated.

1.1.1 Bin Flow Patterns

Following the definitions of Jenike, there are two basic modes of flow, mass flow and funnel flow. These are illustrated in Figure 1.1. Each mode has its own advantages and disadvantages and it is important that designers and operators of bins be aware of their individual characteristics.
Figure 1.1 Flow Patterns in Symmetric Funnel Flow and Mass Flow Bins.
<table>
<thead>
<tr>
<th>MASS FLOW</th>
<th>FUNNEL FLOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total bin contents live</td>
<td>Unless outlet size exceeds critical rathole dimension a considerable percentage of the contents may be non-reclaimable.</td>
</tr>
<tr>
<td>Flow pattern predictable and reliable.</td>
<td>Flow pattern is variable and difficult to predict. Depends on the time history of bin operation since last emptied.</td>
</tr>
<tr>
<td>Outlet size to prevent cohesive arching and is relatively small.</td>
<td>Last in, first out flow pattern promotes segregation, product deterioration, bin corrosion in dead regions, flooding of fine powders.</td>
</tr>
<tr>
<td>Wall loads more predictable when flow pattern is symmetric.</td>
<td>Feeders are larger and more expensive than mass flow.</td>
</tr>
<tr>
<td>First - in, first - out flow pattern; required when segregation, product deterioration are problems or fine powders are to be handled.</td>
<td>Wall loads difficult to predict, especially if bin and/or flow pattern is non-symmetric.</td>
</tr>
<tr>
<td>Requires steep smooth hoppers with protection of hopper walls from impact wear and corrosion.</td>
<td>Capable of storing large quantities of bulk solid which can be gravity reclaimed if free-flowing.</td>
</tr>
<tr>
<td>Detailing of bin structure important to ensure mass flow is maintained.</td>
<td>Bin wear can be a problem if flow pattern causes high velocities down a segment of the bin wall. This situation is promoted by outloading chutes or incorrectly designed feeders.</td>
</tr>
<tr>
<td>Abrasive wear of hopper may be a problem with some bulk solids.</td>
<td></td>
</tr>
<tr>
<td>May be difficult to achieve satisfactory geometry for large storages, without requiring excessive heights.</td>
<td></td>
</tr>
<tr>
<td>Hopper wear and flow problems can occur if feeder design prevents mass flow operation.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1: Characteristics of Mass Flow and Funnel Flow Bins.
as these can have a significant effect on bin performance. Some of these characteristics are summarised in Table 1.1. In mass flow the bulk material is in motion at substantially every point in the bin whenever material is drawn from the outlet. The material flows along the walls of the bin and hopper (i.e. the tapered section of the bin) forming the flow channel. Mass flow occurs when the hopper walls are sufficiently steep and smooth and there are no obstructions to flow, such as abrupt transitions or inflowing valleys.

Funnel flow (or core flow), on the other hand, occurs when the bulk solid sloughs off the surface and discharges through a vertical channel or pipe which forms within the material in the bin. This mode of flow occurs when the hopper walls are rough and the slope angle (α) is relatively flat. The flow is erratic with a strong tendency to form stable pipes which obstruct bin discharge. When flow does occur, segregation takes place, there being no remixing during flow. It is an undesirable flow pattern for many bulk solids, however, it has advantages of minimal bin wall wear, being less costly and having reduced height requirements than for similar tonnage mass flow designs.

Mass flow bins are classified according to the hopper shape and associated flow pattern. Typical mass flow bins are shown in Figure 1.2. The two main types are conical hoppers, which operate with axisymmetric flow, as in Figure 1.2(a), and wedge-shaped or chisel-shaped in which plane flow occurs, as in Figure 1.2(b). In plane flow bins the hopper half angle α is approximately 10° larger than that for corresponding conical hoppers. Therefore, they offer larger storage capacity than for a conical hopper for the same headroom, although this advantage is sometimes offset by the long slotted opening which can cause uneven feed problems. The transition hopper, which has plane flow sides and conical ends, offers a more
Figure 1.2: Mass Flow Bin and Hopper Shapes.

Note: For Wedge and Pyramid Hoppers, valleys should have generous radii or fillets.

\[ L \geq 3B_p \]
acceptable opening slot length, and allows bin diameters larger than slot outlet length. Pyramid-shaped hoppers, while simple to manufacture, are undesirable in view of the build-up of material that is likely to occur in the inflowing valleys which represent high wall friction regions.

The limits for mass flow depend on the half angle $\alpha$, the wall friction angle $\phi$ and the effective angle of internal friction $\delta$. In the case of conical hoppers the limits for mass flow are clearly defined and quite severe, as illustrated in Figure 1.3. Plane flow or wedge shaped hoppers have similar limits for mass flow but these are much less severe [3,4].

Funnel flow bins are characterised either by squat hopper proportions or flat bottoms. For funnel flow bins to operate satisfactorily it is necessary for the opening size to be at least equal to the critical pipe dimension $D_f$. This will ensure that the material will not form a stable pipe but rather one which will always collapse and allow complete or acceptable discharge. However, for many materials the minimum pipe dimension $D_f$ is very large, rendering funnel flow bins impractical. This is certainly the case, for many coals which, at higher moisture levels, are known to have critical piping dimensions of several metres.

Where large quantities of the bulk solid are to be stored, the expanded flow bin, as illustrated in Figure 1.4, is often an ideal solution. This bin combines the storage capacity of the funnel flow bin with the reliable discharge characteristics of the mass flow hopper. It is necessary for the mass flow hopper to have an entry diameter at least equal to the critical piping dimension $D_f$ at the transition with the funnel flow section of the bin. This ensures that the flow of material from the funnel flow or upper section of the bin can be fully expanded by the mass flow hopper. The expanded flow bin concept may also be used to advantage in the case of bins
Figure 1.3: Wall Slope Limits for Mass Flow in Axisymmetric and Plane Flow Hoppers.
Figure 1.4: Flow Pattern in a Symmetric Expanded Flow Bin.
or bunkers with multiple outlets providing the design and operation ensures that the flow channels of adjacent outlets merge.

1.1.2 Determination of Flow Properties of Bulk Solids

In order to design storage bins and associated handling systems it is essential that the flow properties be determined by the testing of a representative sample. The sample tested consists of the fines of the bulk solid, usually the -2.36mm or -4.00mm fraction. This approach is taken because it is considered that the cohesive strength of a bulk solid can be attributed to the fines content. For a material to shear and flow the cohesive strength of the fines must be exceeded to allow the shearing action between the coarser fraction to take place.

The following flow property tests provide the designer with such parameters as:

- Flow Functions (FF) for instantaneous and simulated time storage conditions at rest for low and high consolidation pressures. The flow functions provide a graphical representation of the variations in bulk solid strength with the changes in major consolidation stress occurring under storage and flow conditions.
- Effective Angle of Internal Friction ($\delta$).
- Static Angle of Internal Friction ($\phi_s$).
- Kinematic Angle of Wall Friction ($\phi$) for different bin wall materials and surface finishes.
- Bulk Density ($\rho$) as a function of consolidation pressure.

The flow properties listed above are determined using a Jenike-type Direct Shear Tester except for the bulk density variation which is determined using the Jenike Compressibility Tester. The flow properties are generally expressed as a function of the major consolidation stress or pressure since design procedures to determine critical bin and hopper geometries take
account of the variation with major consolidation stress. Figure 1.5 presents the general form and trends of the flow properties with major consolidation stress. Details of the procedures used for flow property testing are given in References [3, 4].

1.1.3 Determination of Bin Geometry

Once the various flow properties have been obtained it is then possible to determine the required bin shape to provide mass flow, funnel flow or expanded flow.

Based on the operating constraints and the bulk solid characteristics indicated by the flow properties, the particular form of storage bin must be decided. Often in more recent times, industry has required the design of new storage facilities to provide mass flow operation. This is a misconception; funnel flow or expanded flow concepts can be successfully utilised provided attention is paid to the principles of bulk solids flow and the relevant flow properties. The use of mass flow facilities is more expensive than a corresponding funnel flow installation in terms of the required headroom for a given volume (due to the steep hopper walls), the installation of low wall friction liners in the hopper, the high stress loadings at the transition and often higher feeder loadings, and the extra attention required for the construction, installation and maintenance of the internal surfaces.

A decision flow chart has recently been developed by Carson [5], and is presented in Figure 1.6. This procedure details the correct priority of the available design options to ensure the most economical storage facility is achieved. Unfortunately, for the handling of coal, particularly with high fines content and moisture content, the extremely large ratholing diameters
Figure 1.5: Typical Coal Flow Properties.
Figure 1.6: A Procedure to Design Bins and Feeders (Carson[5]).
encountered and the threat of spontaneous combustion, usually precludes
the use of funnel flow designs. For these reasons the design procedure for
funnel flow bins will not be included. Details on funnel flow design are
presented in References [3, 4].

1.1.4 General Design Procedure for Mass Flow Geometry

The aim of mass flow design is to determine the hopper
geometry, in particular the hopper half angle $\alpha$ and the opening size $B$, so
that a stable cohesive arch cannot form over the outlet and that the entire
contents of the bin are in motion when discharge occurs. Two parameters
are important: firstly the 'flow function', $FF$, representing the strength of
the material as previously described, and secondly the 'flow factor', $ff$, which describes the stress condition in the hopper during flow. The flow
factor is given by:

$$ ff = \frac{\sigma_1}{\sigma_f} $$

(1.1)

The flow factor is represented as a ray from the origin (with a
slope of $\tan^{-1}(\frac{\sigma_1}{\sigma_f})$), and is shown, together with the flow function, in Figure
1.7. The flow factor depends on the wall friction angle $\phi$, the hopper half
angle $\alpha$ and the effective angle of internal friction $\delta$. The determination of
the flow factor is described in Reference [3] which also presents the
associated flow factor charts.

By utilising a flow-no flow concept (Figure 1.7), the strength of the
bulk solid (as represented by the flow function), is compared with the
stresses imposed by the hopper (represented by the flow factor). Referring to
Figure 1.7, flow will occur when the major stress acting at the abutment of
the cohesive arch $\sigma_1$ imposed by the hopper exceeds the unconfined yield
stress of the bulk solid $\sigma_c$ causing the cohesive arch to fail.
Figure 1.7: The Flow - No Flow Criteria for Mass Flow Hopper Design.
The critical value of $\bar{g}_1$ occurs at the intersection point of the flow factor and the flow function. If the flow properties of $\phi$ or $\delta$ vary with $\sigma_1$, an iterative procedure must be carried out until $\bar{g}_1$ converges to the critical value.

The minimum outlet dimension $B$ is defined by:

$$B = \frac{\bar{g}_1 H(\alpha)}{\rho g} = \frac{\sigma_1}{\rho g} \frac{H(\alpha)}{h}$$

(1.2)

The function $H(\alpha)$ depends on the outlet shape and hopper half angle $\alpha$ and is presented graphically in Reference [3]. In practice the opening size should be made larger than the above calculated minimum value of $B$ in order to achieve a required flowrate or to allow a degree of conservatism for variation in the bulk solid flow properties from those tested. Variations in material flow properties due to moisture content and storage time can significantly influence the hopper geometry.

It is common for wall yield loci to have a convex upward curved shape. This leads to an angle of wall friction that is pressure dependent, as the major consolidation stress $\sigma_1$ increases, the wall friction angle $\phi$ decreases. Since the major consolidation stress increases with the distance measured upward from the hopper outlet, advantage may be taken of the corresponding decrease in $\phi$ by increasing the hopper half angle $\alpha$. This characteristic can also be exploited by increasing $\alpha$ for increasing outlet span of the hopper as required by other design constraints. A design graph detailing the variation of $\alpha$ with $B$ trend is presented in Figure 1.8 for a typical black coal.

1.2 CONCLUDING REMARKS

This study investigates two major aspects of the design procedures for mass flow storage facilities for hard black coal. The first involves assessment of the degree of influence of various physical variations of coal
Figure 1.8: Design Graph for the Variation of Hopper Wall Slope with Outlet Dimension (for values of B Greater than the Critical).
samples on the subsequent flow properties. Flow property testing can be quite time consuming and expensive, particularly for large testing programs, (as might be required for a storage bin at an export coal loading facility). Identification of the most influential parameters will thus reduce the testing required and allow the development of standard hopper design rules.

The second aspect addressed is the current design procedures used in the determination of mass flow hopper geometries. Although this technology has now been available for the past thirty years, utilisation and exposure to industry has been limited, due to somewhat complicated manual design procedures or the inability to effectively apply computer techniques. This work details the development of manual hopper design nomograms and computer aided design programs to help address the abovementioned shortcomings.

Literature surveys of relevant published material have been included in the respective chapters to aid the continuity and presentation of this study.
CHAPTER 2

EXPERIMENTAL INVESTIGATION OF THE FLOW PROPERTIES OF BLACK COAL

2.1 INTRODUCTION

This study is concerned with the flow properties of hard black coal which make up the major portion of Australia's steaming and coking coals for the domestic and export markets. Coals below the rank of sub-bituminous, such as brown coal and lignite will not be included.

The literature survey commences with published literature prior to development of the Jenike theories through to the present.

2.2 LITERATURE SURVEY AND IDENTIFICATION OF VARIABLES

The handling and storage of coal has always presented industry with problems of unreliable flow, spasmodic feeding and blocking of bin outlets. For many years solutions to these problems were based on mechanical devices, ranging from sledge hammers and air lances through to vertically moving chains and vibrators. Presented below in chronological order is a review of the literature detailing past studies with special reference to papers concerning coal handling studies.

Early attempts of measuring the physical properties of coal were frustrated because no general theory of gravity flow had been developed and the application of soil mechanics testing equipment was too insensitive to quantify the small stresses acting in cohesive arches. As a result, studies such as those of Wolf and Hohenleiten [6] and Legget [7] concentrated on the use of models to explore the mechanics of bulk solid storage and flow, most findings generally being inconclusive. However, these studies did identify
the importance of the surface moisture content and the fines content of coal in leading to flow blockages. This agreed with findings in industry, for example Legget notes that flow blockages occurred at the plant in question after a certain moisture content was exceeded (6%). The bins used during this era were generally of the funnel flow design, and commonly had asymmetrically located outlets. Because these designs were far outside the regions of mass flow (Figure 1.3) complete emptying would often not occur for any combination of bin lining material, outlet dimension or the addition of vibrators. With regard to improving the flow of coal from bunkers before the development of the Jenike theory, one finds in the literature such comments as 'the slope of the hopper is not a determining factor' and 'expensive bunker linings are unnecessary since they do not lead to flow [7].

A notable study conducted on the handling of coal smalls was reported by Hall and Cutress [8]. This study was hampered similarly by the non-existence of a theory of gravity flow and sensitive laboratory instruments. In measuring the fundamental physical properties of several coals by triaxial tests, the results indicated only slight differences, for materials which were known to behave quite differently in practice. Since, previously, there had not been a standard method of measuring handleability, they developed what has become known as the Durham Cone Index. This index is equal to the time required to empty a small vibrated conical hopper, the results for a given sample being found to be reproducible. The tests also indicate, for different samples, significant differences in the measured index corresponding to the known differences in the flow properties of the respective samples. Variables of the coal samples considered included the fines content (-500 μm), the moisture content, the rank of the coal and the effect of addition of some quantities of oil. Conclusions noted from the study in terms of the Durham Cone Index were that for all coals tested the discharge time increases with moisture content
to a maximum then decreases, and the value of the maximum time reduces and occurs at a lower moisture content with decreasing rank. Decreasing the fines content decreased the discharge time to empty at all moisture contents and considerably reduced the maximum value.

In addressing the observed trend of discharge time with moisture content, the authors provide a qualitative explanation in terms of the levels of moisture film between the coal particles, ie. the variation from the pendant to funicular condition and from funicular to capillary states of moisture.

Although the Durham Vibrating Cone is still used, the method only gives an indication of flowability for comparison between samples where only one variable is changed. It is difficult to quantify the effect of two or more variables on the samples' flowability. For the method to have a more practical use, a background of experience is required to relate the discharge time from the vibrating cone to actual plant performance.

Two recent studies, Mikka and Smithan [9] and Crisafulli et al. [10] have utilised the Durham Cone in assessment of coal handleability of Australian black coal. In the case of Mikka and Smithan, the influence of moisture content, particle size distribution, mineral content and coal preparation matter reagents on handleability were investigated. Considering the influence of coal particle distribution the handleability was assessed by both the Jenike shear cell (assessment based on outlet dimension $B_c$ of a conical stainless steel bin) and the Durham Cone (assessment based on discharge time). This study concluded the most significant variable affecting the handleability of washed coal to be the particle distribution. For coals containing little or no fine particles (-500μm), handleability was found to be insensitive to moisture content. However, at high levels of fines the handleability was found to be extremely sensitive to moisture content.
Investigations by Crisafulli *et al.* [10] used the Durham Cone to assess the extreme effect of moisture content on the handling of Walloon coal from Queensland. This coal was particularly difficult to handle for moisture contents above 9%, due to the high clay content (bentonitic types) and its friable nature (Hardgrove Grindability Index, HGI, of 33).

At around the same period of the work of Hall and Cutress, Jenike was developing his theory of gravity flow and the required experimental procedures to measure the flow properties. These are covered in the University of Utah Engineering Experiment Station Bulletins [1-3]. A major feature in the work of Jenike is the testing of the fines, justified by recognising that the large particles move bodily while the material shears across the fines. The coarse particles are a passive agent which do not develop shear strength without the fines to bind them. He also stipulated testing of the *worst representative* sample, in terms of physical parameters such as moisture content, temperature and time storage at rest, to determine the flow properties for bin design.

Using an annular shear tester (as compared to the direct shear tester of Jenike), Jones [11] applied the theory of Jenike in investigating the factors of moisture, particle size and ash content on the flow properties of several British coals. His results indicated the most significant factor to be the fines content (-63 μm considered) with ash content and moisture (moisture content ranging from 0.5 to 7.6% free moisture only considered) having negligible effect. Although this study was also designed to establish a reliable handleability index, and, considered the Durham Vibrating Cone, the flow function FF (from Jenike) and the Power Index 'n' (from the Warren Spring Equation describing yield loci) no recommendations were presented except to indicate disadvantages of the Durham Cone discharge time.
A report compiled by Foster-Miller Associates [12] in 1981, considering the increase of effective bulk density of coal mine car loads by vibration included a section submitted by Jenike and Johanson Inc. on the results of flowability tests of the coals considered. For comparison of the tested coals, the flowability was expressed as the minimum outlet diameter required for a conical mass flow bin for unobstructed flow. This provided a useful index which can be readily related to existing plant designs. The significant effect of moisture content on the flowability of coal was noted. From a series of tests on two coals for a range of moisture contents, the flowability varied from free-flowing for moisture contents below 5%, to required outlet dimensions of 4 to 7 feet in diameter for unobstructed flow at the higher levels considered (15 - 22%).

It is apparent from the literature that moisture content is a major factor affecting the flowability of coal. As stated by Royal and Costello [13] only the surface moisture of coal directly affects the cohesion and friction parameters. They considered methods of measuring the surface moisture of coal (including air drying, heated ventilated oven and microwave) and included preliminary correlations between surface moisture and the flow properties of three coals (of lignite, sub-bituminous and bituminous rank). Findings of the report state no correlation was found between surface moisture and the flow test data. However, it is considered that this was due to the wide range of coal rank considered and the low moisture levels considered (typically 0 - 4% surface moisture). An important aspect raised in [13] was the action of weathering and slacking, where coals stored in stockpiles achieving a marked decrease in flowability over time.

The flow properties of Australian coals has recently been investigated by Leung and Osborne [14]. They determined the flow properties of four coals, namely, Tarong, Millmeran, Callide and Blackwater using a Jenike Direct Shear Tester. The major conclusions noted were the
significant effect on the flow properties of the moisture content (7 - 21% considered), the sample fines content (212 μm) and the period of consolidation at rest (2 days considered). It was also reported that the method of crushing should have no effect on the flow properties since little difference in particle sphericity could be measured between particles crushed by jaw and roller crushers. From a comparison of the four coals considered, Blackwater presented the stronger coal, with no significant differences between the other three.

Further consideration of the effects of moisture on the handling of coal has been investigated by Day and Hedley [15] who developed a computer simulation model. They noted from previous studies that cohesion increases, passes a maximum and decreases as a function of increasing moisture content. The computer model has enabled the cohesion effects to be quantified in terms of the particle distribution and the angle of contact between the water surface and the granular material.

A study [16] for the ETSI pipeline project in the USA (concerned with the slurry transport of sub-bituminous coal), considered the handling and storage problems of dewatered coal. Due to the fine particle sizing (finer than comparable railed coal) and the moisture content it was realised significant levels of cohesive strength could be achieved and must be taken into account when designing bin and hopper outlets. The dewatered pipeline coal had a design surface moisture content of 9 - 10% and particle distributions of up to 23% passing a 45μm sieve. Lower moisture contents could not be tolerated due to dust problems. Flow property testing of the coal for increased moisture contents levels showed an increasing trend of hopper outlet dimension for both instantaneous and time storage conditions ranging from 1 foot to 4 feet diameter for 18%.
The effectiveness of chemical additives to enhance the flow characteristics of coals under high moisture contents was also investigated. Considering water absorbent polymers (which reduce the apparent surface moisture) and surfactants (which reduce the cohesive strength of the water film binding particles) both were found to effectively improve flow of coal from hoppers. However, in view of their expense they were considered unwarranted as the relevant flow property variation had been taken into account in the design of the hoppers.

Reviewing the above literature, the most influential variables appear to be the free surface moisture content, the particle distribution (more specifically the fines content) and the time storage at rest. This concurs with experience gained from industry. Variables affecting the flow properties of coal can be considered under two groups, the physical characteristics of coal and secondly, the characteristics imposed on the coal from operating conditions and equipment. The first group includes the variables of coal rank, maceral constituents, particle shape and ash content.

Variables that can be considered under the second grouping of external influences include the use of chemical additives (for dust suppression or increased flowability), time consolidation at rest, the addition of moisture, the industrial processes of mining, washing and crushing in determining the particle sizing, and the variation of different angles of wall friction for different lining materials (a change of only a few degrees can lead to the discharge pattern changing from mass flow to funnel flow).

Arnold et al. [17] recently completed an extensive testing program to determine the influence of several of the above variables on the flow properties of black coal from the Southern Coalfield, Sydney Basin of New South Wales. The experimental results were also applied to the
determination of the mass flow hopper geometry parameters of hopper slope and outlet span allowing the influence of the variables to be further assessed. The most significant variables were found to be the moisture content, particle top size of test samples and time consolidation at rest.

The most recent and comprehensive review of the available literature relating to the successful handling and storage of coal has been compiled by Wood [18]. The major findings of this report are that moisture content and particle size are the major variables affecting coal flowability. These two factors influence considerations such as the packing of the coal particle assembly, size segregation during storage and flow.

Obviously the difference in flow properties between lignite and anthracite requires no clarification; however, the variation caused from the changes in rank from sub-bituminous, high volatile bituminous, medium volatile bituminous and low volatile bituminous is more difficult to identify. The variations of particle shape, constituents and friability are interrelated due to the over-riding influence of the physical characteristics of the macerals on such properties. The identification of these trends is made more difficult because of the heterogenity of the coal constituents, such that no general trends can be observed between coal basins, between coal seams or, in extreme cases, the daily operation of mines.

2.3 A BRIEF DISCUSSION OF THE ILLAWARRA COAL MEASURES

Coal samples from the Southern Coalfields (Illawarra Measures) of New South Wales were used for the flow property testing program to assess the influence on the flow properties of the various factors highlighted by the literature survey.

The Illawarra coal measures cover the south-eastern segment of the well known Sydney Basin. Geologically the coal measures are of
Permian Age [19] and lie on the Shoalhaven group with Triassic rock covering the coal. The measures form what is known as the Southern coalfields and range in thickness from less than 150 metres in the south near Dapto to over 300 metres in the north at Helensburgh [20,21]. Referring to Figure 2.1 where it can be seen that there are many coal seams in the measure, only four however are mined commercially; namely the Bulli, Balgownie, Wongawilli and Tongarra Seams [22].

Characteristics of each of the coal seams are as follows [20,23].

- **Bulli.** This seam is identifiable over most of the coalfield and is the most extensively mined. It consists essentially of clean coal reaching 4 metres thick in the north and thinning to 0.3 metres in the south. The coal produced is a low volatile type with medium to high ash content. It is a prime coking coal and is categorised [24] as SAA No. 4a22(2) to 4b43(3).

- **Balgownie** Consists of unbanded clean coal reaching over 1.5 metres thickness in the extreme north east but steadily decreases to less than 0.3 metres south of Macquarie Pass. The coal from this seam is a prime coking coal, low to medium volatile type with medium ash content. It is categorised as SAA No. 4A43(2) to 4b43(2).

- **Wongawilli** This seam extends over the whole coalfield and ranges in thickness from 6 metres in the south to 15 metres in the north-east, however, over most of the southern coalfield it is in the range of 9 to 10.5 metres. The seam consists of coal plies of varying qualities separated by bands of carbonaceous and tuffaceous shales. The coal gained from this seam is a medium volatile coking coal, with medium to high ash content. It is very reactive and ideally suited for blending in large proportions with high rank coking coal. It is classified as SAA 4B44(3) to 634(4).
Figure 2.1: Stratigraphic Cross-Section of the Illawarra Coal Measures of the Southern Coalfields [20].
• **Tongarra** This seam is a base member of the Illawarra coal measures and varies in thickness from 1.2 to 6.7 metres. It is best developed in the Tongarra-Avondale areas. The coal is of a low to medium volatile type with medium to high ash content (below 20%). It is a strong coking coal.

The coal from the Southern Coalfields has the highest rank in New South Wales and as such is in high demand for both the local steel industry and for export markets [22]. The coal is of a bituminous rank, although in some areas higher rank coals exist. The coal rank increases slightly from the south to the north of the coalfields [25].

The Illawarra collieries from which coal samples were obtained (locations are detailed in Figure 2.2) are listed in Table 2.1, along with the respective coal seams mined. As indicated in this table, most coals tested were Run of Mine (ROM) samples collected from the raw coal circuit, usually after the primary breaker.

### 2.4 SAMPLE PREPARATION AND FLOW PROPERTY TEST SPECIFICATION

For convenience of sample collection and to remove such considerations as rank variation and ash content (to some extent) from the test program, coals from the Illawarra region were considered initially. From each colliery sampled, up to three major sub-samples were divided and prepared for testing. The following sub-samples were prepared: 100% minus 1.00mm, 2.36mm and 4.00mm. Considerations for the selection of these particle top sizes were:

- The -2.36mm sample was utilised as a datum measurement, since this is the present standard top size used for the flow property testing of bulk solids.
Figure 2.2: Location of Collieries where Coal Samples were obtained for the Flow Property Testing Program [23]
<table>
<thead>
<tr>
<th>Colliery</th>
<th>Coal</th>
<th>Seam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coalcliff</td>
<td>Product</td>
<td>Bulli</td>
</tr>
<tr>
<td>South Bulli</td>
<td>Run of Mine</td>
<td>Bulli and Balgownie</td>
</tr>
<tr>
<td>Huntley</td>
<td>Run of Mine</td>
<td>Wongawilli</td>
</tr>
<tr>
<td>Metropolitan</td>
<td>Run of Mine</td>
<td>Bulli</td>
</tr>
<tr>
<td>Appin</td>
<td>Run of Mine</td>
<td>Bulli</td>
</tr>
<tr>
<td>Westcliff</td>
<td>Run of Mine and Product</td>
<td>Bulli</td>
</tr>
</tbody>
</table>

Table 2.1 Details of Coal Samples used in the Flow Property Testing Program.
In recent times a trend has developed using a sample top size of -4.00mm to allow a less conservative assessment of the flow properties. It is assumed that the larger particle size does not effect the validity of shear measurements. This sample top size has particular application in the testing of bulk solids that have a wide range of particle sizes as would occur for ROM coal. Comparison with the -2.36mm results would be useful in highlighting relative trends with the -4.00mm results.

The finer fraction sample was included to indicate the trends in the flow properties for bulk solids with high proportions of fines. The -1.00mm sample was considered as providing a realistic upper bound for wall friction values and the flow functions. This trend of finer coal is occurring in industry due to changes in mining and coal preparation techniques. As noted by Nicol et al. [26] the current trends indicate that fine coal (-0.5mm) now makes up the greater proportion of raw coal output, in some instances up to 40% of preparation plant feed.

The sized sub-samples were generally tested at four different total moisture contents (expressed on a wet basis): Air Dried (generally 1 to 2.5%), 6%, 10%, and 15%. For the coals tested, it was generally found that above 15% moisture content the samples became saturated, with free water drainage. Also, 15% was generally the upper limit of moisture content for commercial handling operations for hard black coal.

The following flow property tests were carried out on individual coal sub-samples. Using a Jenike-type Direct Shear Tester:

- Instantaneous yield loci to provide the instantaneous flow function and effective angle of internal friction (δ).
• Time yield loci to provide the time flow function for a specified time of consolidation at rest and the static angle of internal friction ($\phi_i$). The standard time consolidation period for tests was 72 hours.

• Wall yield loci to provide the kinematic angle of wall friction between typical bin wall materials and the bulk solid. Typical materials included rusty mild steel, bright mild steel, bright stainless steel (304-2B) and Pactene (UHMW Polymer). The wall friction tests undertaken were for instantaneous conditions only, and did not attempt to determine changes in wall friction due to either time consolidation at rest or deterioration of the wall surface when in constant contact with the coal.

Using the Jenike Compressibility Tester:

• Bulk density as a function of consolidation pressure

The particle size distributions of the samples were determined by sieve analysis using the procedures detailed in BS 1796 : 1952 [27]. A sieve analysis was conducted on the as received coal sample before any sample dividing occurred. For preparation of the sub-samples, the as received sample was brought to an air dried condition prior to being divided into the required number of samples by the Cone and Quartering technique to ensure samples had essentially the same particle distribution. Each sample was then sieved to provide the required top size of the particle distribution. In the preparation of the samples no grinding or crushing was carried out to generate more fines, or to bring the sample within the required top size.

It must be noted that although the samples had the same top size, variation existed in the actual particle distributions between colliery samples. This is in accordance with current flow property testing practices where the sample is prepared by removing that part of the material larger
than the required top size and the remaining distribution is tested in its *as received* distribution. At a latter stage, effort was directed to ensuring the same particle distribution and moisture contents were similar between different samples.

The particle distributions of the coal samples tested are presented in Rosin-Rammler Distribution format in Figures B.1 to B.24, including the *as received* coal sample particle distribution. The Rosin-Rammler Distribution has the characteristic form:

\[
R = 100 e^{-\left(\frac{X}{\bar{X}}\right)^n}
\]  

where

- \( R \) = % weight retained on sieve aperture
- \( X \) = sieve aperture under consideration
- \( \bar{X} \) = the size modulus
- \( n \) = the size distribution constant.

A major advantage of the Rosin-Rammler Distribution is that for broken coal, sieve data can be represented by a straight line and notated by the two parameters \( \bar{X} \) and \( n \). This distribution form was derived to model the brittle fracture of isotropic materials such as coal, providing no sieving and no size separation has occurred. A disadvantage, however, with this distribution form is that experimental scatter is always reduced by taking logarithms, and so taking logarithms twice can lead to inaccurate conclusions regarding particle distribution data.

The discussion provided by Winegartner [28] highlights the advantages of correlating and presenting particle sizing information using the Rosin-Rammler Distribution form. In particular the straight line form can be conveniently used to solve a range of coal handling problems dealing with breakage and degradation and trends in the fines proportion of coal
stocks. Examples of the output from a computer program developed to determine the Rosin-Rammler distribution are included in Appendix B for the coal sample particle distributions for the flow property tests. The agreement of the sieve data with the Rosin-Rammler format is well demonstrated, particularly for the ROM coal samples.

Although no attempt was made to ensure the test samples had similar distributions, it is interesting to note how similar many of the samples were after preparation. This occurred for the -2.36mm and -4.00mm samples eg. comparison of Figures B.10, B.14 and B.18.

2.5 EXPERIMENTAL RESULTS AND DISCUSSION OF FLOW PROPERTIES

2.5.1 Instantaneous Flow Function and Time Flow Function

The ability of a bulk material to flow is dependent on the strength developed by the material due to consolidation and whether as a result of this strength, the material is able to form a stable arch or pipe within the bin. The unconfined yield strength is a measure of the material's strength at an unsupported free surface and is a function of the major consolidation stress:

$$\sigma_c = f(\sigma_1)$$ (2.1)

The instantaneous flow function is a derived property, which is determined from the instantaneous yield loci. These loci are determined by shearing samples of the coal in a Direct Shear Tester for various consolidation loads and represent the properties of the bulk solid relevant to the state of continuous flow. The instantaneous yield loci simulate the failure states for overconsolidated samples prepared at various consolidation pressures and can be represented by a family of lines on the State Boundary Surface of the bulk solid, Figure 2.3. The instantaneous yield
Figure 2.3: The State Boundary Surface for a Bulk Solid.
loci as conventionally depicted in Figure 2.4, represent a projection of the lines on the State Boundary Surface, onto the $\tau - \sigma$ plane. Although the yield loci depicted on the state boundary surface represent ideal conditions, observations made concerning them are helpful as guides for interpreting the actual experimental data. While from a theoretical viewpoint, shear testing is well developed, significant variation in results can occur due to different operators and techniques used for interpretation of results. Consequently standardised testing and interpretation techniques have been developed which minimise operator dependent variations.

Details of the Standardised Procedure is presented in Appendix A. This procedure has been used as the basis of the Draft Australian Standard DR 86111: Flow Properties of Coal [29].

Figure 2.5 details the method of obtaining the coordinates for the flow function from the instantaneous yield loci. The flow function is a plot of the variation of the unconfined yield stress ($\sigma_c$) versus the major consolidation stress ($\sigma_1$). With respect to the comparison of results, because the determination of bin design for reliable flow relates directly to the flow function, this property will be discussed in preference to the yield loci.

The low pressure flow functions determined from the experimental tests are presented in Figures C.1 to C.30. Straight lines have been curve fitted to the data by a computer program described in Chapter 7. The flow function can then be described by the intercept on the vertical axis and the gradient or slope. To analyse trends, a useful technique is to approximate the critical design point for mass flow design, as proposed by Jenike [3] from his flow - no flow criterion, and discussed by Arnold et al. [4]. This critical point represents the stress conditions above which a stable arch
Figure 2.4: Instantaneous Yield Loci.

Figure 2.5: Instantaneous Flow Function (Coordinates obtained from the Instantaneous Flow Function).
cannot form, and is determined from the intersection of the flow function with the relevant flow factor.

Experience has shown that for practical mass flow bin geometries the hopper flow factor exists in the range of $ff = 1.0$ to $ff = 1.3$. These flow factors have been included on the flow function graphs to allow a direct appreciation of the coal strength in this particular design range.

The major influence of the sample moisture content is evident from the figures. The instantaneous flow function of the air dried samples approaches that of a simple bulk solid (flow function passing through the origin), with little influence due to the sample top sizes. This indicates an essentially free flowing bulk solid with negligible arching capabilities.

With an increase of moisture content to 6% total moisture, a dramatic increase in the cohesion and subsequent rise in the unconfined yield stress is displayed. At moisture levels of 10% and 15% the unconfined yield strengths attainable continue to increase.

The figures indicate that the strength for some 15% samples are reduced from the 10% level, while for other samples the opposite trend applies. The gradient of the flow functions provide no definite trends except those of the 15% samples are generally less than the 10% or 6% levels. The higher coal strengths of the 15% samples are due to the high levels of cohesion.

The three sample top sizes show little influence on the flow function for the moisture contents of air dried and 6%. The results from the different coals tested are similar. However, for the 10% and 15% samples the effect of the finer -1.00mm samples leading to stronger flow functions is readily observed. Figures C.21, C.22, C.25 and C.26 compare the flow functions from different collieries for -2.36mm and -4.00mm samples. The
flow functions of the -2.36mm samples at 10% and 15% display less variation than the respective results determined for the -4.00mm test samples. From the figures the range of unconfined yield strength for the -2.36mm sample at 10% is approximately 1.5 to 5.0 kPa and 2.5 to 5.5 kPa for 15% moisture content. The range for the -4.00mm samples is approximately 1.5 to 5.0 kPa for 10% and 2.0 to 5.0 kPa for 15%. Comparison of the -2.36mm and -4.00mm results indicate similar values and ranges although the -4.00mm results were expected to be less than the -2.36mm sample.

Substantial increases in strength occurred for the -1.00mm samples compared to the other two sizes, but only at the 10% and 15% moisture contents. Comparison of Figure C.8 with C.9 for Appin ROM coal and Figure C.11 with C.12 for Westcliff ROM coal indicates that the -1.00mm results can be 1.0 to 1.5 kPa higher than the -2.36mm values over the range of the displayed flow factors.

Table 2.2 presents a summary of the mean value and standard deviation (bracketed) of each of the flow properties at three selected values of $\sigma_i$ (2.5, 5.0, 7.5kPa). Referring to this table, the effect of the moisture content coupled with the sample particle top size, on the instantaneous flow function is well displayed.

Table 2.3 presents an excerpt of Table 2.2 for $\sigma_i = 5.0$ kPa, highlighting $\sigma_c$ values, bracketed values refer to the standard deviation. This table indicates that with increasing moisture content, both $\sigma_c$ and the respective standard deviation increase, the largest values of each occurring for the -1.00mm sample. Considering the effect of the particle top size relative to the -2.36mm sample the $\sigma_c$ values are 3.97 kPa and 4.37 kPa for the 10% and 15% moisture contents respectively. Compared to these values the -1.00mm values are +14.6% and +17.8%, and for the -4.00mm results -1.8% and -6.2%.
Table 2.2: Summary of the Mean Flow Property Values from the Experimental Flow Property Testing Program (Mean Value (Standard Deviation)).

<table>
<thead>
<tr>
<th>Property</th>
<th>-1.00mm Test Sample</th>
<th>-2.36mm Test Sample</th>
<th>-4.00mm Test Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_e$ (kPa)</td>
<td>$\sigma_{oe}$ (kPa)</td>
<td>$\sigma_{oe}$ (kPa)</td>
</tr>
<tr>
<td></td>
<td>$\delta$ (deg.)</td>
<td>$\delta$ (deg.)</td>
<td>$\delta$ (deg.)</td>
</tr>
<tr>
<td></td>
<td>$\rho$ (g/m$^3$)</td>
<td>$\rho$ (g/m$^3$)</td>
<td>$\rho$ (g/m$^3$)</td>
</tr>
<tr>
<td>Rusty MS</td>
<td>35.3 (0.3)</td>
<td>22.6 (0.9)</td>
<td>21.7 (0.8)</td>
</tr>
<tr>
<td>304-2B SS</td>
<td>25.6 (0.6)</td>
<td>23.8 (0.5)</td>
<td>23.2 (0.9)</td>
</tr>
<tr>
<td>Pantece</td>
<td>25.6 (0.6)</td>
<td>23.8 (0.5)</td>
<td>23.2 (0.9)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>6% Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_e$ (kPa)</td>
</tr>
<tr>
<td></td>
<td>$\delta$ (deg.)</td>
</tr>
<tr>
<td></td>
<td>$\rho$ (g/m$^3$)</td>
</tr>
<tr>
<td>Rusty MS</td>
<td>37.5 (1.7)</td>
</tr>
<tr>
<td>304-2B SS</td>
<td>36.2 (3.0)</td>
</tr>
<tr>
<td>Pantece</td>
<td>26.1 (3.4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>10% wb. Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_e$ (kPa)</td>
</tr>
<tr>
<td></td>
<td>$\delta$ (deg.)</td>
</tr>
<tr>
<td></td>
<td>$\rho$ (g/m$^3$)</td>
</tr>
<tr>
<td>Rusty MS</td>
<td>34.8 (3.7)</td>
</tr>
<tr>
<td>304-2B SS</td>
<td>36.0 (3.3)</td>
</tr>
<tr>
<td>Pantece</td>
<td>28.0 (3.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>15% wb. Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_e$ (kPa)</td>
</tr>
<tr>
<td></td>
<td>$\delta$ (deg.)</td>
</tr>
<tr>
<td></td>
<td>$\rho$ (g/m$^3$)</td>
</tr>
<tr>
<td>Rusty MS</td>
<td>37.2 (2.4)</td>
</tr>
<tr>
<td>304-2B SS</td>
<td>32.2 (3.2)</td>
</tr>
<tr>
<td>Pantece</td>
<td>32.7 (1.7)</td>
</tr>
</tbody>
</table>
Unconfined Yield Stress, $\sigma_c$

<table>
<thead>
<tr>
<th></th>
<th>-1.00mm</th>
<th>-2.36mm</th>
<th>-4.00mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% wb.</td>
<td>4.55 (0.70)</td>
<td>3.97 (0.35)</td>
<td>3.90 (0.48)</td>
</tr>
<tr>
<td>10% wb.</td>
<td>4.55 (0.70)</td>
<td>3.97 (0.35)</td>
<td>3.90 (0.48)</td>
</tr>
<tr>
<td>15% wb.</td>
<td>5.15 (1.24)</td>
<td>4.37 (0.54)</td>
<td>4.10 (0.65)</td>
</tr>
</tbody>
</table>

Table 2.3: Variation of Unconfined Yield Stress, $\sigma_c$, with Moisture Content and Sample Top Size (at $\sigma_1 = 5.0$ kPa).
Included in Appendix C are the time flow functions, determined for the coal samples except at the air dried moisture content. The time flow function (determined from the time yield loci tests) provides an indication of the increase of the unconfined yield stress above instantaneous levels occurring from periods of consolidation at rest.

The time flow functions indicate that for all samples increases in the unconfined yield stress above the instantaneous value occurred. This means that the 'flowability' of the material is reduced after periods of storage at rest, thus requiring the hopper geometry parameters (essentially the critical outlet dimension) to be altered from the instantaneous condition to ensure no cohesive arching. For the moisture contents tested it was generally found that for particular sample, the time flow function had a similar (or slightly steeper) gradient to the instantaneous flow function.

At 6% moisture content the time flow function was generally 0.2 to 0.4 kPa higher than the instantaneous flow function. As noted for the instantaneous flow function, there was little influence of the particle top size on the strength of the time flow function. Substantial increases in the unconfined yield stress occurred for the 10% and 15% moisture contents, particularly for the -1.00mm samples.

At these moisture contents increases of 0.5 to 1.5 kPa above the instantaneous $\sigma_c$ values were typical. Table 2.4 (an excerpt from Table 2.2) highlights the range of values of $\sigma_{ct}$ for $\sigma_1 = 5.0$ kPa. The results display an increasing trend of $\sigma_{ct}$ and standard deviation with increasing moisture content except for the -4.00mm sample at 15%. The extremely high values of the -1.00mm sample compared to the -2.36mm results is again apparent. Compared to the -2.36mm values of 4.70 kPa and 5.05 kPa for 10% and 15% respectively, the -1.00mm is +13.8% and +20.8% and for the -4.00mm sample -1.1% and -18.8%.
Table 2.4: Variation of Unconfined Yield Stress, (Time Storage Conditions), $\sigma_{ct}$ with Moisture Content and Sample Top Size (at $\sigma_1 = 5.0$ kPa).

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>-1.00mm</th>
<th>-2.36mm</th>
<th>-4.00mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% wb.</td>
<td>3.25 (0.31)</td>
<td>3.24 (0.47)</td>
<td>3.02 (0.53)</td>
</tr>
<tr>
<td>10% wb.</td>
<td>5.35 (0.48)</td>
<td>4.70 (0.39)</td>
<td>4.65 (0.80)</td>
</tr>
<tr>
<td>15% wb.</td>
<td>6.10 (0.95)</td>
<td>5.05 (0.73)</td>
<td>4.10 (0.65)</td>
</tr>
</tbody>
</table>
2.5.2 Effective Angle of Internal Friction

The effective angle of internal friction, $\delta$, is slope of the Effective Yield Locus (EYL). The EYL is a ray from the origin tangent to the Mohr principal stress circles representing continuous yield or flow. The value of $\delta$ is influenced by the sample top size and the major consolidation stress; however, the primary factor is the moisture content. A comparison of the $\delta$ variations for the coals tested is presented in Appendix D.

Figures D.1 and D.2 compare the $\delta$ variation of seven -2.36mm coal samples at 10% and 15%. The trend of reducing $\delta$ with increasing $\sigma_1$ is shown, and although there is scatter (approximately 55° to 70°) similar values were determined for samples of 10% and 15% moisture content.

Comparison of the $\delta$ results for the Bulli Seam collieries (Metropolitan, Appin and Westcliff) display similar values for both the higher moisture content samples, (Figure D.3). The range in this case is approximately 8°. As depicted in Figures D.4 and D.5 the amount of variation in $\delta$ is influenced by the moisture content. Air dried samples tend to have little variation with $\sigma_1$ with typical values being in the range of 44° to 48°. The slight increase in moisture to 6% causes $\delta$ values to increase to 55° to 60°, with the reduction in $\delta$ quite rapid at low $\sigma_1$ values. At 10% and 15% moisture content the $\delta$ variations are similar and lie in the range of 60° to 70°. Generally $\delta$ values increase with reduced particle top size as displayed in Figures D.6 to D.8. The -1.00mm $\delta$ values are typically 3 to 5% above the larger -2.36mm and -4.00mm samples, which are generally similar. Table 2.5 presents a summary of the mean $\delta$ values and the standard deviation (bracketed) for $\sigma_1 = 5.0$ kPa. These values display the similarity of the -2.36mm and -4.00mm results and the influence of increasing the moisture content on increasing $\delta$. The increased $\delta$ values of the -1.00mm sample relative to the -2.36mm is also shown to become
<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>-1.00mm</th>
<th>-2.36mm</th>
<th>-4.00mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Dried</td>
<td>44.9 (2.0)</td>
<td>45.9 (1.2)</td>
<td>46.2 (2.1)</td>
</tr>
<tr>
<td>6%</td>
<td>53.5 (1.3)</td>
<td>55.6 (3.1)</td>
<td>54.4 (4.1)</td>
</tr>
<tr>
<td>10%</td>
<td>64.5 (3.4)</td>
<td>62.3 (3.1)</td>
<td>62.0 (3.2)</td>
</tr>
<tr>
<td>15%</td>
<td>68.2 (4.6)</td>
<td>63.8 (4.4)</td>
<td>63.5 (2.0)</td>
</tr>
</tbody>
</table>

Table 2.5: Variation of Effective Angle of Internal Friction, $\delta$, with Moisture Content and Sample Top Size (at $\sigma_1 = 5.0$ kPa).
apparent at the higher moisture contents of 10% and 15%. The standard deviation of the values appears relatively constant irrespective of the particle size or moisture content.

### 2.5.3 Static Angle of Internal Friction

The static angle of internal friction, $\phi_t$, is slope of the time yield locus, determined at the tangent point with the unconfined Mohr stress circle. The results for $\phi_t$ show considerable scatter and the least identifiable trends compared to the other flow properties considered. This is partly attributable to problems in the determination and interpretation of the time yield loci. A comparison of the $\phi_t$ variations for the test samples are presented in Figures E.1 to E.10. The figures indicate the high values of $\phi_t$ typical of moist coal ($35^\circ$ ranging to $50^\circ$). The variation of $\phi_t$ with $\sigma_1$ is usually constant or slightly increasing although for some samples there is a decreasing trend.

Results presented in Figures E.1 to E.6 for the ROM and product coal testing program indicate the 10% moisture content samples have generally higher values than the 15% samples ($\phi_t$ values of $40^\circ$ - $46^\circ$ compared with $37^\circ$ - $41^\circ$ respectively).

Considering the -4.00mm results from the Bulli Seam coals (Figure E.4) the 10% and 15% results display a range of approximately $15^\circ$ at low values of $\sigma_1$. There is no general trend between the collieries with the particular moisture content (10% or 15%) having varying degrees of influence, although many of the sample results lie in the range of $43^\circ$ to $47^\circ$. The influence of the sample top size on $\phi_t$ values is displayed in Figures E.2 and E.5. For both figures the finer -1.00mm sample produces higher values, however, there is no clear trend between the -2.36mm and -4.00mm results.

Table 2.6 (an excerpt from Table 2.2, for $\sigma_1 = 5.0$ kPa) presents the overall influence of the particle top size and moisture content on $\phi_t$. 
Table 2.6: Variation of Static Angle of Internal Friction, $\phi_t$, with Moisture Content and Sample Top Size (at $\sigma_1 = 5.0$ kPa).

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>$\phi_t$ (at -1.00mm)</th>
<th>$\phi_t$ (at -2.36mm)</th>
<th>$\phi_t$ (at -4.00mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% wb.</td>
<td>39.9 (3.6)</td>
<td>42.7 (3.7)</td>
<td>44.1 (2.4)</td>
</tr>
<tr>
<td>10% wb.</td>
<td>43.4 (3.6)</td>
<td>42.4 (3.0)</td>
<td>44.3 (4.4)</td>
</tr>
<tr>
<td>15% wb.</td>
<td>47.1 (4.3)</td>
<td>41.2 (1.5)</td>
<td>42.9 (4.4)</td>
</tr>
</tbody>
</table>

Static Angle of Internal Friction, $\phi_t$
The $\phi_t$ values listed lie in the $40^\circ - 44^\circ$ range irrespective of the particle top size or moisture content, except for the -1.00mm 15% sample. This particular value indicates the extreme increases in $\phi_t$ possible for the combination of fine particle content and high moisture content.

2.5.4 Wall Yield Locus and the Kinematic Angle of Wall Friction

The wall friction test determines the friction characteristics of the flow of bulk solids on various wall materials. From the resulting wall yield locus the kinematic angle of wall friction $\phi$ between the bulk solid and the wall material, under varying consolidation pressures may be determined.

References [1,2] highlight the importance of the wall yield locus in ensuring mass flow and slip of the bulk solid along the walls. It is important that conditions intended for the bin wall should be closely modelled for testing purposes. Thus the testing of steel samples with a milled surface are of little benefit since no bin would be lined with a steel with a machined surface but rather a cold rolled or hot rolled finish. This comment also applies somewhat to the testing of stainless steel lining plate whose roughness (as indicated by the $R_a$ value) increases with the sheet gauge for the same surface finish grade.

Recently there have been several comprehensive studies relating to wall friction, indicating an appreciation of the importance of this flow property in mass flow design. Work by Ooms and Roberts [30], ter Borg [31], and Dau [32] have attempted to quantify the influence of the many variables acting at the wall material/bulk solid interface. Examples of these factors include the surface topography of the wall material, relative hardness between the bulk solid and the wall, and the effects of time consolidation and extended exposure.
The importance of correctly assessing the wall friction for mass flow design is well illustrated by reports of *silo quaking*, by Rappen and Wright [33] and Fang *et al.* [34]. Silo quaking is the action of a bulk solid switching between mass flow and funnel flow cyclically on discharge from bins. This generates extreme vibrations which can not only effect the performance of the bin but also the structural integrity of the structure. A suggested reason for silo quaking [33] is the selection of hopper wall slopes that are to close to the design boundaries of Jenike [3] between mass flow and funnel flow.

The importance of wall friction will be further discussed in latter chapters when considering alternative hopper design techniques and the development of standardised design rationale.

Of the many wall lining materials that are utilised in industry and that could be considered for testing, the program was restricted to three different materials, rusty mild steel, 304-2B Stainless Steel (1.5mm gauge) and Pactene. The reasons for this restricted selection were:

- Too large a number of materials would substantially increase the testing time and effort for each coal sample considered.
- Experience with coal over a number of years had indicated that 304-2B stainless steel is one of the best performing materials to line coal bin hoppers [35]. It usually has the lowest friction angles and has a stable surface finish when left in contact with damp coal for extended periods of consolidation at rest.
- Rusty mild steel was included due to its common application as a bin wall material and also because it generally produces the upper bound on friction angles (comparable to rough concrete).
- Pactene was selected to indicate typical values and trends representative of the range of Ultra High Molecular Weight
(UHMW) polymers that are presently marketed as lining materials for bin hoppers and transfer chutes.

Microscope photographs of the three wall material samples are presented in Plate 2.1. The rusty mild steel sample had a typical rough surface due to rusting, with pits up to 0.3mm deep. The 304-2B stainless steel and the UHMW Pactene had the standard 'as supplied' surface finish.

As previously mentioned in Chapter 1, for cohesive bulk solids such as coal, the kinematic angle of wall friction is often not constant, but varies as a function of the consolidation pressure (due to either a curved wall yield locus or an adhesion component at zero normal stress) and the effective angle of internal friction of the particular sample. Figure 2.6 displays the procedure for determining \( \phi \), utilising the outer intersection point (representing the arched stress field) between the wall yield locus and the Mohr stress circle passing through the required consolidation stress \( \sigma_1 \).

Comparison between wall yield loci provide only superficial indications since the effect of adhesion, the effective angle of internal friction and the position of the wall yield locus cannot be accurately assessed, particularly with regard to values of \( \phi \). To provide a direct relation between \( \phi \) and \( \sigma_1 \) the geometric relations presented in Figure 2.6 have been solved mathematically and incorporated into a computer program. Chapter 7 presents details of the program which determines the variation of \( \phi \) with \( \sigma_1 \) and the minimum value of \( \sigma_1 \) yielding a real solution (ie. when the Mohrs stress circle of \( \sigma_1 \) is tangent to the wall yield locus). The subsequent graphical output, which displays the variation of \( \phi \) versus \( \sigma_1 \) is presented in Figure 2.7. Comparison of the \( \phi \) variations for different wall materials and coal samples using this presentation is more effective, particularly in the low stress region which is relevant to mass flow hopper design.
Plate 2.1: Microscope Photographs of Wall Materials Used in Wall Friction Tests (x32 Magnification)

(a) Rusty Mild Steel.

(b) 304 - 2B Stainless Steel.

(c) Pactene.
Figure 2.6: Determination of the Kinematic Angle of Wall Friction.
Figure 2.7: Kinematic Angle of Wall Friction Variation.
The $\phi$ variations from the testing program are presented in Figures F.1 to F.28. For the two coal samples an additional sample of -0.5mm was incorporated into the wall yield locus testing program to further investigate the influence of particle size. Referring to these figures, the first apparent feature, particularly for the higher moisture content coal samples is the variation of $\phi$, reaching quite high values at low $\sigma_1$ values. Thus in designing for bulk solid flow, for example transfer chutes or mass flow hoppers $\phi$ values may be substantially greater than those utilised in the structural design of bins. This fact has recently been emphasised by Schwedes [36] in discussing the German Din 1055 structural bin design code.

The variation of $\phi$ for each of the wall materials, for the range of coals tested is presented in Figures F.1 to F.6. Concerning rusty mild steel, at both 10% and 15% the product coals (Westcliff and Coalcliff collieries) have lower $\phi$ values than the ROM coal samples. There appears to be no other trend for the range of coal samples tested, the range of $\phi$ for $\sigma_1 > 4kPa$ is approximately $6^\circ$. For the 304-2B stainless steel the range of $\phi$ is smaller particularly for the 10% result, where for $\sigma_1 > 4kPa$, $\phi$ is approximately $18^\circ$ to $22^\circ$. Pactene displays good agreement between the coal samples at 15% (range of $3^\circ$ for $\sigma_1 > 4kPa$) but at 10% the results are scattered with a range of approximately $4^\circ$ to $6^\circ$. There appears to be no major influence of the increased moisture content from 10% to 15% for $\phi$ values for Pactene.

Figures F.7 and F.8 indicate that air dried coal has a lower wall friction than the moist coal samples for rusty mild steel (of approximately $3^\circ$). However, for samples with moisture contents in the range of 6% - 15% similar $\phi$ values were displayed for each wall material. The stainless steel tends to show the opposite trend, where the wall friction is reduced from the air dried sample values compared to moist coal. The coal at 6% moisture content shows a higher friction value than for other moisture samples (refer to Figures F.9 and F.10).
The $\phi$ variations which are vertically asymptotic to the wall friction axis for values of $\sigma_1 < 1.5\text{kPa}$ indicate severe adhesion tendencies between the bulk solid and the wall material. This is displayed for the Westcliff coal (Figure F.9) where the strongest adhesion exists for the 6% moisture level. This trend is also repeated in Figure F.10 but not to the same degree.

The Pactene displays a lower wall friction for the air dried and 6% samples compared to the stainless steel because of the reduced adhesion tendencies. With increasing the moisture content above these levels the wall friction of the Pactene increases approximately $3^\circ$ to $4^\circ$ above the air dried values (Figures F.11 and F.12).

The influence of the particle top size on the wall friction for rusty mild steel, Pactene and stainless steel at 10% and 15% is displayed in Figures F.13 to F.18. The rusty mild steel results show the -0.5mm sample to have the higher friction of $32^\circ$ for both 10% and 15%. Both the -1.00mm and -2.36mm levels are shown to have similar friction levels but the wall friction for the -4.00mm sample lies between the variation of the -1.00mm and the other two particle sizes for both moisture levels. This could indicate disturbances between the larger coal particles passing over the steel surface.

The Pactene demonstrates a reduction of wall friction with increasing particle top size. For both the 10% and 15% samples the -0.5mm sample has $\phi$ values approximately $3^\circ$ to $4^\circ$ greater than the -2.36mm, -4.00mm samples which are similar. The results for the stainless steel are displayed in Figures F.17 and F.18. The 10% sample $\phi$ variations show similar $\phi$ values for the particle sizes of -0.5mm, -1.00mm ($20^\circ$) and -2.36mm, -4.00mm ($17^\circ$). The finer samples are approximately $3^\circ$ greater than the -2.36mm and -4.00mm samples.
Although, at 15% moisture content, the -0.5mm sample again has the highest friction, the next lower $\phi$ variations occur for the -1.00mm and -4.00mm samples, the lowest values being for the -2.36mm sample. This scatter, with a range of some 2$^\circ$ is within experimental error and would indicate similar $\phi$ values may be determined for the -1.00mm to -4.00mm sample range, particularly at higher $\sigma_1$ values for the stainless steel.

Table 2.7 (an excerpt of Table 2.2) displays the variation of $\phi$ for 304-2B stainless steel for $\sigma_1 = 5.0$ and 7.5 kPa, for a combination of particle top sizes and moisture contents. Only the stainless steel results are repeated because of its common application as a hopper wall liner. Bracketed figures refer to the standard deviation. The table indicates that for the -2.36mm and -4.00mm samples $\phi$ is essentially constant for the various moisture contents when $\sigma_1 > 5.0$kPa. The -1.00mm values for $\sigma_1 = 5.0$ and 7.5kPa show substantially greater $\phi$ values than determined for the other samples (particularly at 6% and 10% moisture contents) because of increased adhesion of the coal to the wall surface.

2.5.5 Bulk Density Variation

For the design of storage bins the variation of bulk density with increasing consolidation stress is required. The lower values are required for the determination of hopper outlet dimensions and feeder loads, while high values of stress are used when predicting bin wall pressures.

The results from the Jenike Compressibility Tester may be represented conveniently by the power equation:

$$\rho = \rho_0 \left( \frac{\sigma_1}{\sigma_0} \right)^b ; \sigma_1 > 0$$  (2.2)

where

$\rho = \text{solids bulk density corresponding to the major consolidation stress } \sigma_1.$
### Kinematic Angle of Wall Friction, $\phi$, for 304-2B Stainless Steel

<table>
<thead>
<tr>
<th>Sample</th>
<th>-1.00mm</th>
<th>-2.36mm</th>
<th>-4.00mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.0kPa</td>
<td>7.5kPa</td>
<td>5.0kPa</td>
</tr>
<tr>
<td>Air Dried</td>
<td>22.6(0.9)</td>
<td>21.7(0.8)</td>
<td>22.1(4.1)</td>
</tr>
<tr>
<td>6%wb</td>
<td>29.7(3.4)</td>
<td>25.8(2.4)</td>
<td>22.4(2.4)</td>
</tr>
<tr>
<td>10%wb</td>
<td>25.1(1.0)</td>
<td>22.2(0.8)</td>
<td>20.4(1.3)</td>
</tr>
<tr>
<td>15%wb</td>
<td>23.8(2.0)</td>
<td>21.3(1.8)</td>
<td>20.2(1.4)</td>
</tr>
</tbody>
</table>

Table 2.7: Variation of Kinematic Angle of Wall Friction, $\phi$, for 304-2B Stainless Steel, with Moisture Content and Sample Top Size (at $\sigma_1 = 5.0$ kPa).
\( \rho_o \) = solids bulk density corresponding to the arbitrary major consolidation stress \( \sigma_o \). (The respective values of \( \rho_o \) and \( \sigma_o \) are normally selected as the centroid of the experimental data as determined from the statistical curve fitting procedure.)

\( b \) = compressibility constant for the particular bulk solid.

Thus, for any bulk solid, values of \( \sigma_o \), \( \rho_o \) and 'b' are required. By plotting the above variation on logarithmic axes it is apparent that 'b' is the gradient of the resulting straight line and is a measure of the compressibility of the bulk solid. The testing program results indicate that the variation of bulk density with consolidation pressure is accurately modelled by the above equation. Utilisation of this equation allows a more consistent appraisal of bulk density under different loading states. Other researchers [37] have used terms such as tapped, aerated, lightly packed etc. which involve disadvantages in determining when to apply the various terms and does not allow the variation with consolidating stress to be appreciated [38].

A summary of the experimental bulk density variations is presented in Figures G.1 to G.14. These figures present the bulk density variations derived from the power equation form, curve-fitted to the experimental data.

The following trends are apparent from a comparison of the results:

- For the collieries of the Illawarra region, the range of bulk density is 150 - 200 kg/m\(^3\) about mean values of approximately 800 kg/m\(^3\) for 10% samples and 900 kg/m\(^3\) for 15% moisture content samples (\( \sigma_1 = 7.5 \text{ kPa} \), Figures G.1 and G.2). This range is significant since for many of the collieries, coal is mined from the same seams using similar extraction methods. The maximum bulk density values (at higher consolidation stresses \( \sigma_1 \): 50 < \( \sigma_1 \) < 75 kPa) for
10% samples are 1000 kg/m\(^3\) and approximately 1050 - 1075 kg/m\(^3\) for 15% coal.

- The bulk density generally increases with sample top size for coal at the same moisture content. As an example Figures G.3 and G.4 display the bulk density variation of Westcliff Product coal at 10% and 15%. As depicted the -2.36mm and -4.00mm samples produce the maximum values. An overall analysis of Table 2.2 indicates the -4.00mm samples have bulk density values 10 - 12% greater than the -1.00mm sample at 10% and 5 - 6% greater at 15% moisture content (based on \(\sigma_1 = 7.5\) kPa).

- The bulk density variation with moisture content for samples of the same particle top size is presented in Figure G.5 to G.8. In the range of \(\sigma_1: 5 < \sigma_1 < 15\) kPa the bulk density for air dried coal is higher than moist coal at 6% and 10% and approximately the same order as the 15% samples.

- The air dried samples usually represent the least compressible state ('b' values of the order of 0.02) compared to those of higher moisture contents. The variation of 'b' is significantly affected by the sample moisture content. The values of 'b' increase from the air dried condition values to a maximum which is often at the 10% level and reduces for the 15% test sample.

Table 2.8 provides a summary of the variation of 'b' with moisture content for the -2.36mm coal samples.

### 2.6 COMPARISON OF THE FLOW PROPERTIES FOR THREE COALS WITH SIMILAR PARTICLE DISTRIBUTIONS.

This flow property testing program was instigated to highlight differences that might occur for test samples having similar particle distributions at similar moisture contents (maximum moisture content
Compressibility Constant 'b'.

<table>
<thead>
<tr>
<th>Coal</th>
<th>AD</th>
<th>6%</th>
<th>10%</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coalcliff</td>
<td>0.0224</td>
<td>-</td>
<td>-</td>
<td>0.0579</td>
</tr>
<tr>
<td>Huntley</td>
<td>0.0223</td>
<td>0.0555</td>
<td>0.0754</td>
<td>0.0638</td>
</tr>
<tr>
<td>South Bulli</td>
<td>0.0208</td>
<td>0.0604</td>
<td>0.0721</td>
<td>0.0570</td>
</tr>
<tr>
<td>Appin</td>
<td>0.0165</td>
<td>0.0562</td>
<td>0.0711</td>
<td>0.0598</td>
</tr>
<tr>
<td>Metropolitan</td>
<td>0.0220</td>
<td>0.0525</td>
<td>0.0660</td>
<td>0.0499</td>
</tr>
<tr>
<td>Westcliff ROM</td>
<td>0.0194</td>
<td>0.0558</td>
<td>0.0767</td>
<td>0.0533</td>
</tr>
<tr>
<td>Westcliff Product</td>
<td>-</td>
<td>0.0497</td>
<td>0.0670</td>
<td>0.0621</td>
</tr>
</tbody>
</table>

Table 2.8: Variation of the Compressibility Constant, 'b', with Moisture Content and Colliery.
difference between samples was 0.5% wb). The three coal samples were Westcliff ROM, Westcliff Product coal and a Queensland Product coal. Elimination of the influences of particle distribution and moisture content from the results ensured that any differences in the flow property results largely would be due to a combination of the following factors:

- the effect of washed coal product compared to ROM coal samples
- differences in the coal from the two coalfields
- differences in the ash constituents
- differences in the maceral content ratios
- particle shape
- traces of washing mediums retained within samples

The samples used came from two coal basins featuring different characteristics. The Westcliff ROM and Product coal was mined from the Bulli seam, within the Sydney Basin and represents a hard coal (H.G.I. of 56) with a low inherent ash content. The second sample came from the central region of the Bowen Basin of Queensland and represents a very soft and friable coal (H.G.I. of 87).

Samples were prepared as -2.36mm test samples and the flow properties assessed at 10% and 15% moisture contents, representing typical values at which the coal is handled. Figures C.23 and C.24 compare the instantaneous and 3 day time flow functions of each sample. At 10% the Westcliff ROM and Product coals have similar instantaneous and time flow functions. The Queensland sample displays substantially stronger flow functions particularly for the time storage conditions (approximately 0.7 kPa above the Westcliff coal samples). At 15% the increase of the time flow function above the instantaneous is greater compared to the 10% samples, typical increases being 0.8 to 1.8kPa for the range of the displayed flow factors. Figure C.24 also displays the positioning of the instantaneous and
time flow functions into two distinct groups, the stronger time flow functions occurring for the Westcliff Product and Queensland Product Coals.

Comparison of the flow functions with results from other testwork (refer Figure C.21 and C.22) indicate that they are typical of the flow functions determined from other testwork where the sample particle distribution and moisture content was not as closely controlled. These figures indicate the Queensland Product coal to be in the stronger range of the coals tested.

The effective angle of internal friction results displayed in Figure D.9 shows similar trends and values, determined from other flow property testing. The results of the Westcliff ROM and Product coals are similar, with typical values of 60° for 10% and 68° (σ₁ = 5kPa) for 15% moisture contents. The Queensland coal however displays similar values for both moisture contents of approximately δ = 66°. For all the samples at 15%, there was a marked decreasing variation of δ with increasing σ₁, typically 70° to 55° for σ₁: 0 < σ₁ < 20kPa. The φ_e results (Figure E.7) display a similar level of scatter that was found for the other coal sample tests. However, the Westcliff ROM coal samples indicate similar results φ_e = 48° for both 10% and 15% moisture contents. The Queensland and Westcliff Product coal samples displayed lower values of φ_e of approximately 42° - 46°.

The kinematic angle of wall friction results are displayed in Figures F.19, F.20 and F.21 for rusty mild steel, 304-2B stainless steel and Pactene respectively. Generally the results followed similar trends to those displayed from other testwork in regard to moisture content and type of wall material. For each wall material φ values were found to be within a 4° range independent of the moisture content. Average values for φ were found to be 27 - 28° for rusty mild steel, 18° - 20° for stainless steel and 23°
Pactene (\(\sigma_1 = 7.5\) kPa). For two samples, Westcliff ROM (15% moisture content) and Queensland (15% moisture content) the \(\phi\) variation for stainless steel was quite different to the general trend of values noted. The Westcliff ROM was substantially higher (\(20^\circ < \phi < 25^\circ\)), and the Queensland coal below the average (\(\phi: 14^\circ < \phi < 17^\circ\)).

The bulk density variations for coal samples at 10% and 15% moisture contents are displayed in Figure G.9 and G.10 respectively. They display approximately the same form for each sample indicating equivalent values of 'b', the compressibility constant. The results indicate in relative order of decreasing bulk density to be Queensland, Westcliff ROM and Westcliff Product. The bulk density values are also shown to increase 12 - 15% with a moisture content increase from 10% to 15% wb.

Overall the flow properties determined for the three coal samples are typically within the range of values found for similar moisture content coal samples. The Queensland coal sample did indicate stronger flow functions (particularly at 10%) and higher bulk density values, but for the \(\delta\), \(\phi_t\) and \(\phi\) flow properties there were no definite trends. Comparing the Westcliff ROM and Product samples, similar flow properties were found between both samples, although the Product coal displayed a stronger time flow function at 15%.

### 2.7 INFLUENCE OF PARTICLE SHAPE ON FLOW PROPERTIES.

To assess the changes that can occur in the shape of coal particles from handling operations and to investigate the subsequent effect on the various flow properties a sample of Westcliff ROM coal was tumbled in a Friability Drum Tumbler constructed according to ASTM D441 - 45 [39]. The Friability Drum Tumbler simulates coal degradation (such as occurs at transfer points) and allows the determination of a Friability Index for comparison with other coals.
Examination of the samples after tumbling indicates rounding of particles greater than 4.00mm occurred but generally little rounding occurred for the finer particles. Plate 2.2 presents SEM photographs of coal before and after tumbling and indicates that brittle fracture of particles occurred in preference to rounding.

Two samples of Westcliff ROM coal were prepared for flow property testing, one as a -2.36mm control sample and the second, which after tumbling was remixed to the same particle distribution as the control sample. Flow property tests were conducted at 10% and 15% moisture content. Figure C.20 displays the instantaneous and time flow functions of both samples. The tumbled coal is shown to have stronger flow functions (compared to the control sample) however within the range of the displayed flow factors the relative differences are small. The other flow properties of effective angle of internal friction, static angle of friction, kinematic angle of wall friction and bulk density variation indicate similar values to those found from other coal testwork. Figure D.10 shows a typical decreasing trend of $\delta$ with increasing $\sigma_1$ with comparable values occurring for both moisture contents, typically, $\delta = 60^\circ$ (for $\sigma_1 = 5.0kPa$) with a range of 4°. The variation of $\phi_t$ with $\sigma_1$ is presented in Figure E.8 and shows the tumbled coal sample to have higher values above the control sample (typically 4° - 5°) at both moisture contents. For $\sigma_1 = 5.0kPa$, the tumbled coal $\phi_t$ was approximately 42° compared to 37° - 38° for the control sample. At 15% both coal samples displayed an increasing trend of $\phi_t$ with increasing $\sigma_1$ whereas relatively constant values occurred for the 10% sample.

The variation of $\phi$ for Pactene and 304-2B stainless steel is presented in Figure F.22 for the tumbled and control samples at both moisture contents. The characteristic friction values found from other coal tests of 22° for Pactene and 18° for stainless steel are indicated. Comparison between the control and tumbled samples indicate no definite trends with $\phi$
Plate 2.2: SEM Photographs of Westcliff ROM Coal, Control and Tumbled Samples (x250)

(a) Control Sample, 125 x 150 µm.

(b) Tumbled Sample, 125 x 150 µm.
values being within a 3° range for $\sigma_1 = 5kPa$. Figure G.11 displays the bulk density variations for the tumbled and control samples. The 15% tumbled sample is shown to be approximately $50kg/m^3$ greater than the control sample. Typical asymptotic values for the samples are $1020 kg/m^3$, $970 kg/m^3$ and $940 kg/m^3$ for the 15% tumbled, 15% control and 10% tumbled samples respectively. The typical increasing trend of bulk density with increasing moisture content is displayed. Reference to Figure G.15, in providing an overall comparison of the bulk density variations for Westcliff coal indicates that the tumbled sample is typical of the results determined from other tests.

The effect of the sharp angular particles is shown to have only a minor effect on the coal flow properties when comparing the results from the control sample and from other test results. The results show no definite trends that could be attributed to the particle shape. The tumbling operation indicated that coal particles could be expected to generate sharp angular coal fines by brittle fragmentation in preference to abrasion and rounding the coal particles from repeated handling operations.

2.8 FLOW PROPERTIES OF SAMPLES OF FREE CLAY MIXED WITH COAL.

This testing program was instigated to assess the effect of clay mixed with coal samples on the various flow properties in simulating the storage and handling characteristics of high ash content coals. Preparation of the test samples were based on Westcliff ROM coal which was air dried, sieved to -4.00mm and divided into four samples of approximately the same particle distribution. Flow property tests were conducted on two clay types, Kaolin, a non-swelling clay and a swelling clay Bentonite.

Commercial grade Kaolin and Bentonite was added respectively to two samples to increase the ash content from approximately 11% to a
nominal 25%. To the third sample a similar amount of coal fines (-45 μm) was added to indicate the relative effect of the added small particles independent of the chemical effects of the clay. The fourth sample was retained as a control sample to provide a basis for the flow property comparisons.

The physical appearance of the resulting test samples are presented in Plates 2.3 and 2.4 which display SEM photographs of the control and coal with Kaolin samples at two magnifications. The graded particle distribution of the coal particles with typical sharp edges and conchoidal fracture planes contrasts with the appearance of the coal particles embedded in a matrix of clay platelets for the Kaolin and Bentonite samples.

The instantaneous and 3 day time flow functions from the test program are presented in Figures C.27 to C.30. At 5% the flow functions of the clay samples are comparable to the coal plus fines sample. The time flow functions display only a small increase over the instantaneous condition, which was expected for this low moisture content. For 10% moisture content the two clay samples and the control sample had similar instantaneous flow functions with typical values of $\sigma_c: 1.2 < \sigma_c < 2.5$ kPa within the displayed flow factor range while the coal plus fines sample was significantly higher with $\sigma_c$ values in the range of 3.7 - 4.5 kPa. Comparison of the 3 day time flow functions for the clay samples indicate the high values of $\sigma_{ct}$ attainable which are approximately double the instantaneous values.

With increasing moisture contents, the unconfined yield strength continues to increase. For the Kaolin clay sample this increase was such that shear tests were conducted only to a maximum moisture content value of 12.5% due to the strong instantaneous flow functions. The time flow functions for the clay samples at the higher moisture contents indicated the occurrence of a cementing action or 'set' which was relatively insensitive to
Plate 2.3: SEM Photographs of Westcliff ROM Coal (Control Sample) and Coal Mixed with Kaolin.

(a) Control Sample (x285).

(b) Coal Mixed with Kaolin Sample (x285).
Plate 2.4: SEM Photographs of Westcliff ROM Coal
(Control Sample) and Coal Mixed with Kaolin.
the values of $\sigma_1$. The time flow function for 15% Bentonite depicted in Figure C.29 was typical of this action. Figure C.28 displays the time flow functions of the coal plus fines sample leading to comparatively high $\sigma_{ct}$ values with steeply sloping flow functions. Again the $\sigma_{ct}$ values determined for the coal plus fines samples were approximately double those values found for the control sample.

An overall comparison of the flow functions indicates that the clay samples have similar instantaneous flow functions to the control sample up to moisture contents of 10%. Above this level the clay and the coal plus fines samples have similar values which are significantly stronger than the control sample results. Concerning the time flow functions, above 10% moisture content both clay samples displayed extremely strong levels of unconfined yield strengths typically caused by a cementing action. In several instances the clay sample time flow functions were similar to those determined for the coal plus fines samples.

Mikka and Smithan [10] who also tested the influence of Kaolin and Bentonite on the handleability of coal (but for a lower ash content %) found that the non-swelling clay had little influence. However for the swelling clay, Bentonite, handleability deteriorated rapidly above 8%. On this basis, they correctly highlight the significance of the actual clay mineral (for instance Scott and Graham [40] report on the handling problem, coal mixed with montmorillonite) and not just the actual level of clay present.

Considering the effective angle of internal friction, Figure D.11 and D.12 present the results of the four test samples. At 5% moisture content, the clay and coal plus fines samples display similar $\delta$ variations ranging typically from $58^\circ$ to $52^\circ$ for $\sigma_1$: $0 < \sigma_1 < 20$ kPa. At the higher moisture contents a greater variation is indicated (Figure D.12). The control and coal plus fines samples display similar $\delta$ variations which were typical of the values from other moist coal testwork. Comparing the clay samples,
the Bentonite sample displayed constant values of 51° and 55° for moisture contents of 10% and 15% respectively, which were unusually low for such coal samples. The Kaolin sample at 10% displayed a constant value of 8° = 60°, but at 12.5% displayed significantly higher values ranging from 76° to 62° decreasing with increasing σ_t.

Referring to the \( \phi_t \) results, comparison between Figures E.9, E.10 and E.4 (displaying \( \phi_t \) results from other coal testwork) indicate similar values and ranges. Figure E.10 indicates that most \( \phi_t \) results for the four samples gave values in the range of 40° - 48°. There appears to be no definite trend, although the lowest \( \phi_t \) values occurred for the control and coal plus fines 15% samples and the maximum values occurred for the Kaolin clay samples at 10% and 12% moisture contents.

The results of the kinematic angles of wall friction for the three wall materials, rusty mild steel, 304-2B stainless steel and Pactene are presented in Figures F.23 to F.28. Comparing the values for the coal plus fines and control sample, the moisture content is shown to have the greatest effect compared to the effect of the fines content difference between the two samples.

For example, Figure F.24 shows that for stainless steel, the 15% sample has \( \phi \) values 2° - 3° less than the typical 10% values of 18° - 17°. The clay samples of Kaolin and Bentonite have reduced \( \phi \) values compared to those of the control and coal plus fines samples. This is best displayed by rusty mild steel (Figure F.26) and stainless steel (Figure F.27). For the rusty mild steel typical \( \phi \) values from the clay samples (at both 10% and 15%) are approximately 26° compared to the higher values of 30° - 27° for the coal plus fines samples. Figure F.27 for stainless steel displays lower values typically of 15° (particularly for the Bentonite) compared to values ranging from 20° - 18° for the coal plus fines samples. The wall friction values for
Pactene display little variation for the different samples and moisture contents, with $\phi$ values typically being $22^\circ$ with a $2^\circ$ range for $\sigma_1 > 5.0$ kPa.

The clay samples displayed values of bulk density that were 10% - 15% above the control and coal plus fines results, which was expected due to the higher specific gravity of the clay. Figure G.13 displays the bulk density variations at 10% moisture content where the relative order of samples in decreasing bulk density was Bentonite ($1080$ kg/m$^3$), Kaolin ($1010$ kg/m$^3$), and the coal plus fines ($960$ kg/m$^3$) and control samples being similar. The four bulk density variations displayed have similar variation curves indicating similar 'b' or compressibility constants. The results for the 15% moisture content (Figure G.14) display increased values relative to the 10% results, with the maximum Bentonite value of $1150$ kg/m$^3$. There is also a discernible difference between the control and coal plus fines samples of approximately $30$ kg/m$^3$, the coal plus fines variation being the higher result.

Generally, the flow properties of the clay samples are similar to the coal plus fines samples, and indicate reduced handleability compared to the control sample. The most apparent and critical feature of the clay samples is the high cohesive strength displayed by the flow functions for moisture contents in excess of 10%. This is especially prominent when considering the time storage of coals with these characteristics where a strong 'set' or cementing action can occur. Concerning the other flow properties, the $\delta$ and $\phi_t$ variations were generally similar to the results found from other testwork, however the clay samples displayed reduced $\phi$ values for some wall materials and significantly higher bulk density values compared to the control and coal plus fines samples.
2.9 CONCLUDING REMARKS

The investigations reported in this chapter have concentrated on the flow properties of samples of hard black coal from the Southern Coalfields of the Sydney Basin and to a lesser degree the Bowen Basin of south eastern Queensland. The influence of sample variables such as moisture content, particle top size of sample, particle distribution and time consolidation at rest on the various flow properties has been investigated.

Assessment of the various parameter influences is on the basis of the Jenike shear cell tests. This approach has been reported (Mikka and Smithan [10]) as displaying reduced sensitivity in differentiating between the general handleability of coals. This instance is illustrated by coals that contain varying levels of fines in the full size distribution but yield similar flow property results because the test samples have similar 0 x 4mm particle distributions. Utilising the flow properties determined from the shear tests is justified however, as this study is concerned with the design of storage bins.

The most influential parameters were found to be the sample moisture content, values from Air Dried (generally 1 to 2.5%) to 15%wb. being considered, and the sample cut size, as represented by the particle top size of the test samples. The combined effects of moisture content and particle distribution are displayed in Figures 2.8, 2.9 and 2.10 where the variation of the unconfined yield strength (represented by the flow function) with moisture content is presented. This flow property is crucial to the determination of the critical outlet dimension in mass flow hopper design. The variation of $\sigma_c$ with moisture content is apparent, from the characteristics of a simple bulk solid occurring at air dried conditions to maximum strength occurring for moisture contents in the range of 10% - 15%, typically the moisture levels in the fines fraction at which coal is transported and stored. The effect of the increased fines content is depicted
Figure 2.8: Variation of the Instantaneous Flow Function with Moisture Content Based on -1.00mm test sample (Mean Values Displayed).
Figure 2.9: Variation of the Instantaneous Flow Function with Moisture Content Based on -2.36mm Test Sample (Mean Values Displayed).
Figure 2.10: Variation of the Instantaneous Flow Function with Moisture Content Based on -4.00mm Test Sample (Mean Values Displayed).
in Figure 2.8 where at high moisture contents $\sigma_c$ developed may be double the values determined for the two larger particle cut test samples. Comparison between Figure 2.9 and 2.10 present similar results and indicate that the -2.36mm sample does not necessarily lead to conservative flow function results compared to the -4.00mm sample.

A summary of the mean flow property values from the testwork has been presented in Table 2.2 and for the -2.36mm test sample graphically displayed in Figure 2.11. The effect of time consolidation at rest in leading to significant increases in the unconfined yield strength above instantaneous conditions is apparent. The difference between $\sigma_{ct}$ and $\sigma_c$ increases with increasing fines content and moisture content of the sample.

The effective angle of internal friction develops two trends with increasing moisture content, the value of $\delta$ increases and a marked variation of decreasing $\delta$ with increasing $\sigma_1$ (for $\sigma_1: 0 < \sigma_1 < 15$ kPa) occurs. At 15%, typical $\delta$ values range from $60^\circ - 70^\circ$. The static angle of internal friction displayed the least identifiable trends of the flow properties considered, with $\phi_t$ values ranging from $40^\circ - 45^\circ$ for moisture contents of 10% and 15%.

An important aspect involved in the design of mass flow hoppers and transfer chutes is the wall friction value and variation typical of wall lining materials for various physical conditions of the coal (moisture content and particle size distribution). Each wall material has a characteristic $\phi$ value range which varies according to the moisture content and to a lesser extent the particle size distribution. An important feature, particularly regarding the performance of smooth metal lining materials (eg. 304-2B stainless steel) with moist coals is the action of adhesion, and for other wall materials, convex upward wall yield loci which lead to variable angles of wall friction dependent on $\sigma_1$. Figure 2.11 displays the typically high values of $\phi$ which can be developed for 304-2B stainless steel at low $\sigma_1$ levels.
Figure 2.11: Typical Variation with Moisture Content of the Flow Properties Required for Mass Flow Hopper Design (Mean Values from -2.36mm Sample Tests Displayed).
The bulk density variation leads to asymptotic $p$ values for high $\sigma_1$ values. Generally, the maximum $p$ values occurred for the air dried and 15% moisture content samples. The bulk density values decreased from these levels for moisture contents of 10% and 6%.

Other testwork considered the influence of particle shape, and the addition of clay to coal test samples to simulate high ash content coals. Comparison of the flow properties of tumbled coal with a control sample indicate minor influences due to the particle shape. SEM photographs indicated that for repeated handling operations the coal particles would tend to remain angular and fragmented in nature due to brittle fragmentation which occurs in preference to an abrasive and rounding action.

In simulating high ash coals, the flow property testing of coal samples mixed with two clay types (Kaolin and Bentonite) indicate similar flow properties (particularly the instantaneous flow function) to those that would be expected for high fines content coals. Although the clay samples displayed reduced $\phi$ values for some wall materials compared to the control sample, the major feature was the extremely strong time flow functions which occurred for moisture contents above 10%. Several of these time flow functions displayed a 'cementing' action where the variation of $\sigma_{ct}$ was only slightly influenced by $\sigma_1$. These results are pertinent to those coals containing certain clays. Several researchers [11,40] comment that these coals present no handling problems immediately after mining and when relatively dry. However, when the coal is exposed to the weather for periods of time, moisture is absorbed and the coal degrades, with the clay component forming a sticky matrix.
CHAPTER 3

SENSITIVITY OF MASS FLOW HOPPER GEOMETRY PARAMETERS TO COAL FLOW PROPERTIES

3.1 INTRODUCTION

The mass flow critical hopper geometry parameters have been determined for the coal samples whose flow properties were tested and reported in the previous chapter. Review of the hopper geometry parameter values provides a tangible indication of the influence of the various flow property trends, and gives an overall appreciation of the effect of such variables as sample moisture content, particle top size and time consolidation at rest can have on the design of mass flow storage bins.

The critical hopper geometry consisting of hopper wall slope, $\alpha$, and outlet dimension, $B$, for axisymmetric and plane flow hoppers has been determined for both instantaneous and time conditions for the wall lining materials of rusty mild steel, 304-2B stainless steel and Pactene. The calculation of these parameter values was achieved by a computer program utilising the Jenike method [3, 4] and described briefly in Chapter 1.

The values of the critical hopper geometry parameters are presented in tabular form in Tables H.1 to H.21. Table 3.1 presents a summary of the critical hopper geometry parameters for all the coal sample tests except for those of the free clay testing program. For each category two values are presented, the first being the mean and the second bracketed value, the standard deviation of the data set. Note, that the mean and standard deviation for each category has been calculated on data sets with different numbers of results.
### Table 3.1: Summary of the Critical Hopper Geometry

<table>
<thead>
<tr>
<th>Parameters</th>
<th>6% Moisture Content</th>
<th>10% Moisture Content</th>
<th>15% Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rusty MS</td>
<td>304-2B SS</td>
<td>Pacene</td>
</tr>
<tr>
<td></td>
<td>Rusty MS</td>
<td>304-2B SS</td>
<td>Pacene</td>
</tr>
<tr>
<td></td>
<td>Rusty MS</td>
<td>304-2B SS</td>
<td>Pacene</td>
</tr>
<tr>
<td>$\alpha_c$ (deg)</td>
<td>2.3 (0.4)</td>
<td>4.0 (-)</td>
<td>13.2 (-)</td>
</tr>
<tr>
<td>$\alpha_{ct}$ (deg)</td>
<td>3.8 (0.4)</td>
<td>7.5 (-)</td>
<td>16.7 (5.4)</td>
</tr>
<tr>
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<td>10.0 (-)</td>
<td>23.8 (9.8)</td>
</tr>
<tr>
<td>$\alpha_{pt}$ (deg)</td>
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<td>17.0 (-)</td>
<td>27.0 (6.1)</td>
</tr>
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<td>$B_m$ (mm)</td>
<td>787.5 (194.5)</td>
<td>820.0 (198.0)</td>
<td>830.0 (235.7)</td>
</tr>
<tr>
<td>$B_{ct}$ (mm)</td>
<td>250.0 (47.7)</td>
<td>277.5 (10.6)</td>
<td>268.3 (59.2)</td>
</tr>
<tr>
<td>$B_p$ (mm)</td>
<td>370.0 (98.5)</td>
<td>417.5 (102.6)</td>
<td>400.0 (108.2)</td>
</tr>
<tr>
<td>$B_{pt}$ (mm)</td>
<td>127.00 (375.6)</td>
<td>1450.0 (499.9)</td>
<td>1456.3 (432.1)</td>
</tr>
<tr>
<td>$B_{ct}$ (mm)</td>
<td>1766.3 (210.2)</td>
<td>2110.0 (232.2)</td>
<td>2048.8 (214.5)</td>
</tr>
<tr>
<td>$B_p$ (mm)</td>
<td>646.3 (193.8)</td>
<td>681.3 (224.3)</td>
<td>685.0 (209.6)</td>
</tr>
<tr>
<td>$B_{pt}$ (mm)</td>
<td>891.3 (109.7)</td>
<td>951.3 (129.8)</td>
<td>943.8 (121.3)</td>
</tr>
</tbody>
</table>

**Bin Geometry**

<table>
<thead>
<tr>
<th>-1.00mm Test Sample</th>
<th>-2.36mm Test Sample</th>
<th>-4.00mm Test Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Rusty MS</td>
<td>304-2B SS</td>
</tr>
<tr>
<td></td>
<td>Rusty MS</td>
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</tr>
<tr>
<td></td>
<td>Rusty MS</td>
<td>304-2B SS</td>
</tr>
</tbody>
</table>

**Program (Mean Value (Standard Deviation)).**

**Parameters from the Experimental Coal Testing.**
Review of the results indicates that the hopper wall slope for plane flow is generally 9° - 11° greater than the axisymmetric hopper slope and for the critical outlet dimension, plane flow values are 40% - 50% of the span required for axisymmetric hoppers.

3.2 INFLUENCE OF MOISTURE CONTENT VARIATION

As the results from Table 3.1 indicate, a substantial variation in the critical hopper parameters (particularly the critical arching dimension) occurs for both axisymmetric and plane flow hoppers as the moisture content varies from air dried to 15%. This variation is due primarily to the increased cohesion and variation of the flow function (ie. $\sigma_c$ and $\sigma_{ct}$).

Coal in the air dried condition behaves as a simple bulk solid, with very small or no critical outlet dimensions. Dimensions are of the order of 150mm and 80mm for axisymmetric and plane flow outlets respectively. In these instances the outlet span is not constrained by cohesive arching but rather to ensure no mechanical arching at the outlet (due to particle interlocking) or to achieve the required discharge rate.

Figures 3.1, 3.2 and 3.3 have been prepared to display the variation in $\alpha$ and $B$ due to moisture content, sample particle top size and time storage. An increase of moisture content to 6% leads to critical arching dimensions in the range of 500mm to 700mm for axisymmetric hoppers and 200mm to 400mm for plane flow hoppers under instantaneous conditions. This is a dramatic increase in span relative to the air dried result, particularly in view of the small increase in moisture content.

At 10% moisture content the outlet span increases above the 6% value by 50% - 60% As indicated in Table 3.1, typical values for the -2.36mm and -4.00mm samples are 1000mm and 500mm for axisymmetric and plane flow hoppers respectively.
Figure 3.1: Variation of the Critical Hopper Geometry Parameters with Moisture Content for -1.00mm Test Samples.
Figure 3.2  Variation of the Critical Hopper Geometry Parameters with Moisture Content for -2.36mm Test Samples.
Figure 3.3: Variation of the Critical Hopper Geometry Parameters with Moisture Content for -4.00mm Test Samples.
An increase in moisture content to 15% leads to only small increases in the critical outlet dimension relative to the 10% results. Generally the increase is of the order of 5% - 10%, however, for some samples the outlet dimensions were smaller than the 10% moisture content values, for example, Westcliff ROM coal, Tables H.10 and H.11.

This occurs because of the influence of the flow functions from each moisture content. Comparison of the flow functions for the 10% and 15% tests shows that similar values of the unconfined yield stress may occur in the $\sigma_1$ range for $ff = 1.0$ to $ff = 1.3$ even though there may be different trends of cohesion and slope of the two flow functions.

For each of the results displayed in Figure 3.1, 3.2 and 3.3, the standard deviation of the critical outlet span increases with increasing moisture content. It can also be seen that the standard deviation of the plane flow outlet spans is approximately 30% - 50% that of axisymmetric hoppers. Considering the results for 304-2B stainless steel from Figure 3.2 and 3.3 for 10% and 15% moisture contents the average critical outlet span for axisymmetric hoppers is 1000mm with a standard deviation of 200 to 250mm. For plane flow hoppers the outlet span is 500mm with a standard deviation of 150mm. The results indicate that the largest values of $B$ required for reliable flow occur for the range of moisture contents at which coal is commonly handled and transported.

The trend of increasing hopper wall slope with increasing sample moisture content is apparent for most wall materials considered. Typical values of $\alpha$ for 304-2B stainless steel for axisymmetric hoppers are $15^\circ$ for 6%, $21^\circ$ for 10% and $22^\circ$ - $23^\circ$ for 15% moist coal. Wall slopes for plane flow hoppers are $20^\circ$ - $25^\circ$ for 6%, $30^\circ$ for 10% and $33^\circ$ for 15% moisture contents. The increasing wall slope trend is directly linked to the reduction of wall friction angle $\phi$ of the stainless steel. This trend is dependent on the
characteristics of the wall material considered. The variation of $\phi$ with $\sigma_1$ with moisture content for other materials may be the opposite, or not as pronounced as that found for the stainless steel (e.g. Pactene, -2.36mm results displayed in Figure 3.1).

For 304-2B stainless steel, $\phi$ reduces with increasing moisture content with the maximum values occurring at 6%. A second factor that leads to a relative reduction in $\phi$ for the wall materials with variable angles of wall friction is the higher value of $\sigma_1$ acting at the critical geometry for 10% and 15% samples. The $\sigma_1$ values correspond with the stronger flow functions and increased outlet dimensions required for reliable operation. The influence of the $\phi$ range typical of each of the wall materials on the subsequent $\alpha$ values is well demonstrated. Referring to Table 3.1 (-2.36mm results) the lower $\phi$ values of Pactene compared to stainless steel leads to the $\alpha$ values being 4° and 10° greater than stainless steel wall slopes for axisymmetric and plane flow hoppers respectively. The higher $\phi$ values of rusty mild steel (usually above 30°) are comparatively insensitive to moisture content levels and lead to the steepest hopper slopes of the wall materials considered. Typical values are 8°-10° for axisymmetric hoppers and 15°-18° for plane flow hoppers.

3.3 INFLUENCE OF PARTICLE TOP SIZE OF TEST SAMPLES

As previously mentioned in Chapter 2, the standard particle top size of coal samples for flow property test samples was -2.36mm. This was increased to the current -4.00mm cut to reduce the degree of conservatism of the hopper outlet spans resulting from the smaller particle cuts. Reference to Figures 3.2 and 3.3 indicates similar values of $\alpha$ and B for the -2.36mm and -4.00mm samples particularly for instantaneous conditions with stainless steel as the wall material. Comparison of these values with
those displayed for the -1.00mm sample in Figure 3.1 shows the significantly different $\alpha$ and B values required for the storage of high fines content coals.

Overall several trends are apparent. The often larger values of the critical arching dimension B from the -1.00mm sample compared to the two larger cuts, is clearly displayed in Figure 3.4. Depending on the moisture content, the mean values of B are 400 - 500mm for axisymmetric hoppers and 300 - 400mm for plane flow hoppers greater than for the other particle cuts. The increased wall friction of the -1.00mm samples is apparent, leading to hopper wall slopes typical 3°- 5° less than the comparable -2.36mm and -4.00 samples. Table 3.1 and Figure 3.1 also display the geometry parameter standard deviations, which are largest for the -1.00mm sample, indicating a greater variability in the results particularly for the 10% and 15% moisture contents.

Similar results between the -2.36mm and -4.00mm values for $\alpha$ and B are indicated including comparable standard deviations. The comparison of the hopper geometry parameters presented in Figure 3.4 indicates the relatively close agreement between these two sample cuts. The greatest variation occurs for the axisymmetric outlet dimension with typical differences of 150mm occurring for outlet spans of 1500mm. The results indicate that the -2.36mm results are not conservative compared to the -4.00mm values. However, often the -4.00mm results present a greater variability which must be balanced against ease of preparation of the test samples.

3.4 INFLUENCE OF TIME CONSOLIDATION AT REST

Chapter 2 has presented the typical increases of the unconfined yield stress above the instantaneous values due to time consolidation. This feature, when applied to the hopper geometry parameters leads to an increase of the outlet span, and often the hopper wall slope, due indirectly
Figure 3.4: Variation of the Critical Hopper Geometry Parameters (Mean Values) with Particle Top Size of Test Samples.
to a reduction in wall friction. The critical outlet dimension must increase to account for the 'set' or increase in the unconfined yield stress from $\sigma_c$ to $\sigma_{ct}$ and ensure that flow will recommence reliably. The hopper wall slope can be increased only for those wall materials that display a variable $\phi$. The increased outlet span leading to increased $\sigma_1$ values and a decrease of $\phi$ can then be utilised by correspondingly relaxing the value of $\alpha$ determined for the instantaneous condition.

The mean $\alpha$ and B values for time storage conditions (3 days) are displayed in Figures 3.1, 3.2, 3.3 and 3.4. As expected the disparity between instantaneous and time storage values of B increases with increasing moisture content and decreasing particle top size. The values of B for axisymmetric hoppers display the greatest increase above instantaneous values, of the order of 500 - 600mm for axisymmetric outlets and 200 - 300mm for plane flow outlets. The -1.00mm results indicate that bin geometries required for the time storage of high fines content coals can reach impractical values. Reference to Figure 3.4 displays critical outlet spans above 2 metres for axisymmetric hoppers while typical outlet dimensions determined from the two larger top size samples are 1500 - 1600mm for axisymmetric hoppers and 800mm for plane flow outlets.

In assessing the increase allowable for the hopper wall slope, only 304-2B stainless steel will be highlighted because of its widespread use as a low friction liner and because of its marked $\phi$ variation with $\sigma_1$ for moist coal. Figures 3.2 and 3.3 display an increase $\alpha$ of typically 2°- 5° above instantaneous values for plane flow outlets. For axisymmetric hoppers $\alpha$ generally increases by a smaller margin of 1°- 3°.

When detailing the hopper geometry for a known period of time consolidation at rest it is essential that the outlet be increased above the critical outlet dimension determined for the instantaneous condition. Failure to account for the increase in B can lead to cohesive arching and the
inability of the bin to reliably discharge. The increase in \( \alpha \) however can be considered as a benefit of increasing the outlet span and be utilised to relax headroom and design constraints, but of course if the instantaneous \( \alpha \) value is used, the bin will obviously operate reliably.

3.5 INFLUENCE OF FREE CLAY IN COAL SAMPLES

The free clay (Kaolin and Bentonite) was added to certain coal samples to simulate the behaviour of high ash content coals and typical hopper geometry parameters required for their storage. The critical hopper geometry parameters based on the various sample moisture contents are presented in Tables H.19, H.20 and H.21.

Comparison of the results indicate that Kaolin requires outlet spans 15 - 20\% greater than the corresponding Bentonite coal samples. Both clay samples have larger outlet spans than the control -4.00mm sample but, more importantly, the values are similar or slightly less than those for the coal plus fines sample. This indicates the importance of particle distribution in influencing the cohesive strength of the coal. Comparison of the outlet spans with Table 3.1 shows that at 10\% moisture content the clay and control samples are less than the mean values determined of 1069mm axisymmetric and 490mm for plane flow outlets (for stainless steel). At 15\% moisture content the outlet spans required for Kaolin are typically 55 - 65\% greater than the mean values of 1076mm and 508mm for axisymmetric and plane flow outlets respectively (for 304-2B stainless steel).

Under time storage conditions the hopper parameters for the clay and coal fines samples lead to impractical values for mass flow. The extremely large outlet spans (2300 - 3200mm for axisymmetric and 1000 - 1500mm for plane flow outlets) are a direct result of the extremely strong time functions for these materials, whereas the mean outlet spans for 304-2B stainless steel from Table 3.1 are approximately 1600mm (axisymmetric)
and 760mm (plane flow). Under time conditions the values determined for the high fines content coal are shown to have larger outlet values than comparable clay samples, reinforcing the importance of particle distribution.

Comparison of the hopper wall slopes for the various samples indicates that similar values occur for the control, high fines samples and the mean values (Table 3.1) and that the clay samples are generally 15-20% greater. The higher $\alpha$ values for the clay samples appears to be the result of two factors, the reduced wall friction due to the clay content and also to the higher $\sigma_1$ values corresponding to the larger outlet dimensions required.

Overall it would appear that high clay content coals can be stored and handled using reasonable mass flow designs, with similar geometries as required for other coals tested. However under the time storage conditions impractical geometries are required for reliable operation (particularly in regard to outlet spans). This indicates that either the period of consolidation should be reduced or other means of storage investigated. The performance of high fines content coal has been highlighted as being similar to the clay samples.

3.6 CONCLUDING REMARKS

From the analysis presented in this Chapter on the influence of the mass flow hopper geometry parameters, the following comments can be made:

- Similar results for $B$ and $\alpha$ were determined for the -2.36mm and -4.00mm samples at 10% and 15% moisture contents. Outlet dimensions based on the -1.00mm sample flow properties were significantly larger, and hopper wall slopes up to $5^\circ$ smaller.
- The maximum outlet dimension for all particle top sizes appeared to occur for moisture contents between 10% and 15%.
This tends to support the observation from general experience that maximum strength occurs at approximately 80% of the sample saturation moisture content.

- Based on the mean values calculated, the plane flow hopper wall slope was generally $9^\circ - 11^\circ$ greater than the corresponding axisymmetric hopper value, and the critical outlet dimension for plane flow 40% - 50% of the value required for the axisymmetric case.
CHAPTER 4

ALTERNATIVE PRESENTATION OF THE DESIGN PARAMETERS FOR MASS FLOW HOPPERS

4.1 INTRODUCTION

The procedure for determining the critical hopper outlet dimension and wall slope for mass flow hoppers by the Jenike method is well established and documented. However, existing traditional presentations relating the bulk solid flow properties of effective angle of internal friction and the kinematic angle of wall friction with the hopper wall slope and flow factor for mass flow are often inconvenient for manual use and present difficulties when included in design programs suitable for microcomputers.

An alternative presentation of the original Jenike flow factor charts has been developed which display only the critical design values in the border region between mass flow and funnel flow. The charts eliminate the need for imprecise parameter interpolations by displaying the required parameters in the form of contours of constant hopper wall slope and critical flow factor as a function of the effective angle of internal friction and the kinematic angle of wall friction.

Although presented in Chapter 1, a brief overview of the Jenike design procedure will be presented along with various methods of displaying mass flow parameters relationships that have been previously developed.

4.2 DETERMINATION OF THE MASS FLOW HOPPER GEOMETRY PARAMETERS.

The Jenike design procedure [3] takes into account the bulk solid
flow properties and the stresses imposed by the hopper, in determining the
genometry parameters of critical dimensions and wall slope. The required
flow properties of the bulk solid describe the variation of strength and
frictional characteristics with consolidation pressure.

Employing a flow-no flow concept, the strength of the bulk solid
(as represented by the flow function) is compared with the stresses imposed
by the hopper (represented by the flow factor). The critical value of $\sigma_1$ occurs
at the intersection point of the flow factor and the flow function. The flow
factor value is a function of the wall friction angle, the effective angle of
internal friction, the hopper wall slope and the shape of the hopper
(axisymmetric or plane flow).

The flow factor, $ff$, and the hopper wall slope, $\alpha$, are design
parameters of the Jenike procedure because, as Equation 1.2 [3] indicates, the
critical outlet dimension is dependent on both these parameters and,
further, the flow factor value is influenced by $\alpha$.

The flow-no flow concept is implemented by approximating the
stress conditions occurring in a converging channel during flow by a radial
stress field according to the relationship:

$$\sigma = \tau S(\alpha)$$  \hspace{1cm} (4.1)

The solution of the set of partial differential equations describing
the radial stress field under specific boundary conditions allows the value of
$S(\alpha)$ to be computed and, hence, the flow factor determined by the relation:

$$ff = \frac{H(\alpha)(1+\sin\delta)S(\alpha)}{2\sin\delta}$$  \hspace{1cm} (4.2)

Jenike computed flow factor values and presented the results in
the well-known series of charts for axisymmetric and plane flow hoppers
[1,3]. These graphs display contours of constant flow factor as a function of
the hopper slope and the kinematic angle of wall friction for specific values of effective angle of internal friction (30° through 70° degrees by 10° increments). Examples of the flow factor charts for axisymmetric and plane flow hoppers (for an effective angle of internal friction of 50°) are presented in Figures 4.1 and 4.2 respectively.

As depicted in these figures, particularly Figure 4.1, the region of the flow factor contours is bounded by a limit. This border represents the limit beyond which the boundary conditions are not compatible with the radial stress field and flow does not develop along the hopper walls. This bound is particularly severe for axisymmetric hoppers and, to ensure that mass flow occurs, Jenike recommends that the wall slope be reduced 3° to 5° from the bound to account for any variation of the wall friction value in practice from the laboratory test values. For plane flow hoppers, however, the boundary is not as stringent, but to prevent the development of excessive non-flowing regions originating from the hopper transition a design limit is suggested (the dashed line, Figure 4.2).

In determining the mass flow hopper geometry, the values of the hopper wall slope and flow factor are determined from these charts for the combination of effective angle of internal friction, the kinematic angle of wall friction and the hopper shape. Although it is possible to minimise the flow factor by suitable selection of the hopper slope for a given wall friction value (and thus optimise the flowability of the hopper [3]), from a practical design viewpoint it is preferable to maximise the hopper wall slope. This is achieved by using values along the suggested design limits for plane flow, or allowing a 3° reduction of wall slope from the mass flow-funnel flow limit in the case of axisymmetric hoppers.

Although the Jenike flow factor charts clearly display the limits of hopper wall slope between mass flow and funnel flow and the respective
Figure 4.1: Flow Factor Chart for Axisymmetric Hoppers, \( \delta = 50^\circ \) (Jenike [3]).
Figure 4.2: Flow Factor Chart for Plane Flow Hoppers, \( \delta = 50^\circ \) (Jenike [3]).
flow factor values along the design boundary, they are disadvantaged by the necessary parameter interpolations required. These are two major problems associated with the parameter interpolations. Firstly, since the charts are presented for specific values of $\delta$, those designs having intermediate values require the parameters of flow factor and hopper wall slope to be adjusted between the respective charts to ensure accuracy. Secondly, due to the troughed form of the flow factor contours in the region of the design limit, determination of the flow factor values can be difficult. For example, consider determination of the flow factor for $\phi$ of $15^\circ$ and $\alpha$ of $40^\circ$ from Figure 4.2.

A clearer indication of the influence of $\alpha$ on the limit of hopper wall slope for mass flow in conical hoppers was presented by Johanson and Colijn [41] (Figure 4.3). This diagram condenses the mass flow limits of the Jenike flow factor charts to one diagram by displaying contours of constant $\delta$ as a function of $\phi$ and $\alpha$. Interpolation of intermediate values of $\delta$ in order to determine the maximum values of $\alpha$ is more convenient than for the Jenike flow factor charts.

Johanson and Colijn [41] also include an alternative series of flow factor charts to determine the flow factor after a suitable hopper wall slope has been selected from Figure 4.3. These charts display contours of constant flow factor as a function of $\delta$ and $\phi$ for the specific $\alpha$ values of $10, 20, \text{and } 30^\circ$. The flow factor chart for a hopper wall slope of $20^\circ$ is depicted in Figure 4.4. Interpolation between the flow factor contours is more convenient in this presentation due to their more uniform nature. However, imprecise flow factor values can arise because of the presentation of the charts in $10^\circ$ increments of wall slope.

Limits on the selection of hopper wall slope have also been prepared for axisymmetric and plane flow hoppers for mass flow by Arnold
Figure 4.3: Hopper Wall Slope Limits for Axisymmetric Hoppers (Johanson and Colijn [41]).
Figure 4.4: Critical Flow Factors for Mass Flow Hoppers, 
\[ \alpha = 20^\circ \] (Johanson and Colijn [41].)
et al. [4] and are presented in Figure 4.5. This presentation utilises the limits proposed by Jenike [3]. Of more benefit, however, particularly in regard to computer applications, are the equations which are given to represent the design limits. For axisymmetric hoppers,

\[
\alpha = 0.5 \left( 180 - \cos^{-1}\left(\frac{1-\sin\delta}{2\sin\delta}\right) - \left[\phi + \sin^{-1}\left(\frac{\sin\phi}{\sin\delta}\right)\right]\right)
\]  

(4.3)

and for plane flow hoppers,

\[
\alpha = \frac{\exp\left[3.75(1.01)^{\delta-30/10}\right] - \phi}{0.725(\tan\delta)^{0.2}}
\]  

(4.4)

for \(\phi < \delta - 3\); \(\phi\) and \(\delta\) in degrees.

Reference to Figure 4.5, however, indicates that for the range of common values of \(\phi\) (approximately 15° to 30°) for mass flow design the maximum bound of \(\alpha\) is relatively insensitive to the variation of \(\delta\). The influence of the effective angle of internal friction on the flow factor has been considered by Jenike [42]. In dealing with plane flow hopper design he notes that the effect of \(\phi\) is minimal on the flow factor value and presents the variation of the flow factor as a function of \(\delta\) (Figure 4.6). Although Figure 4.6 was prepared for \(\phi\) of 25° and \(\alpha\) of 25°, Jenike states that the flow factor variation will be negligible for different design values, thus having little effect on the outlet dimension \(B\) from Equation 1.2.

Carson and Johanson [43] have recently enhanced this concept by adding the flow factor variation with \(\delta\) curve for the axisymmetric case, Figure 4.7. They further comment that the flow factor for both axisymmetric and plane flow hoppers are essentially the same for the same \(\delta\) value (the value of \(\phi\) and \(\alpha\) was not stated in the preparation of Figure 4.7).

### 4.3 ALTERNATIVE PRESENTATION OF THE MASS FLOW HOPPER DESIGN PARAMETERS

A common factor between the various methods discussed in the
Figure 4.5: Wall Slope Limits for Axisymmetric and Plane Flow Hoppers (Arnold et al. [4]).
Figure 4.6: Variation of Flow Factor with Effective Angle of Internal Friction, $\alpha = 25^\circ, \phi = 25^\circ$ (Jenike [42]).

Figure 4.7: Variation of Flow Factor with Effective Angle of Friction (Carson and Johanson [43]).
previous section for the presentation of the flow factor and the hopper wall slope is the need to refer to several graphs in determining a satisfactory design.

Generally, the selection of the mass flow hopper geometry involves the determination of the maximum hopper wall slope allowable for the particular bulk solid flow properties and operating conditions. This necessarily involves selecting design values along the mass flow limits (refer to Figures 4.1 and 4.2) and, as such, the remainder of the bounded mass flow region is of little interest. These areas are only utilised for such tasks as the verification of existing plant designs.

With these factors in mind, an alternative presentation of the mass flow hopper design parameters has been developed and is presented in Figures 4.8 and 4.9 for axisymmetric and plane flow hoppers respectively. These figures display the variation of the flow factor and hopper wall slope in contour form as a function of the kinematic angle of wall friction and the effective angle of internal friction.

The data mesh for the formation of both charts was obtained by utilising the design bound for $\alpha$ (as predicted in Equations 4.3 and 4.4) and the particular values of $\phi$ and $\delta$ to determine the maximum allowable value of $\alpha$. With these three parameter values the respective flow factor was determined using differential equation solution techniques and Equation 4.2. Thus, only the values of maximum $\alpha$ which will ensure mass flow for the respective values of $\phi$ and $\delta$ are displayed.

The following design constraints have been taken into account in determining the data mesh:

- For *Axisymmetric hoppers*, a $3^\circ$ reduction of the hopper wall slope from the radial stress compatibility bound has been used.
Figure 4.8: Alternative Presentation of Axisymmetric Hopper Design Parameters.
Figure 4.9: Alternative Presentation of Plane Flow Hopper Design Parameters.
and the flow factor determined at this margin point.

- For plane flow hoppers, the wall slope limit specified in Equation 4.4 and the constraint of $\phi > \delta - 3$ degrees, has been applied.
- The upper limit of the hopper wall slope is $60^\circ$.

This data mesh lends itself to computer applications for systems that do not have mathematical packages for the solution of differential equations (to determine the flow factor). The values required can be determined by linear interpolation techniques based on the data mesh.

An advantage of this chart format is that a complete overview of the trends of flow factor and hopper wall slope variation with $\phi$ and $\delta$ is presented. Reference to Figures 4.8 and 4.9 indicates the direct influence of $\phi$ on the value of $\alpha$ and the minor effect of $\delta$, particularly for plane flow hoppers. This trend of reducing values of flow factor with the increasing $\delta$ is also well demonstrated. This trend is in agreement with the presentation of Jenike [42], but allows the overall effect of $\phi$ on the flow factor to be appreciated. For a constant $\delta$ value of $50^\circ$ and a range of $\phi$: $5^\circ < \phi < 40^\circ$, the flow factor is seen to vary from 1.25 to 1.22, justifying the assumption of Jenike to neglect the $\phi$ variation in determining an initial measure of flowability.

For a given set of values for $\delta$ and $\phi$, the design parameters of $\alpha$ and flow factor are determined by referencing the intersection point to the plotted contours. Although the contour increments for Figures 4.8 and 4.9 are necessarily coarse to ensure clarity, large chart formats can utilise smaller contour intervals and reduce prorating of values.

Correct interpretation of the data determined from the charts should be stressed. It is important to bear in mind that only the maximum value of $\alpha$ and the respective flow factor value relevant to the traditional
mass flow limits are displayed. Concerning the value of hopper wall slope, the $\alpha$ contour specified the maximum value allowable to ensure mass flow and slip of the bulk solid along the wall. Values of $\alpha$ greater than that specifies can lead to a funnel flow discharge pattern, while a reduction below this value leads to a more conservative design. Reference to Equation 1.2 similarly provides an insight into the variation of the flow factor about the design value. Utilising a flow factor value smaller than the design point will lead to a reduction in $\sigma_1$, a reduced outlet dimension $B$ and, hence, the formation of cohesive arches. Noting that the design point specifies the critical flow factor value, a more conservative design will then result from using an increased value.

The advantages of utilising this presentation to determine the hopper geometry based on the bulk solid flow properties have been noted in the preceding discussions. However, care should be exercised in the verification of mass flow occurring in existing storage facilities. The value of hopper wall slope can be checked knowing $\delta$ and $\phi$ and ensuring that $\alpha_{\text{actual}} < \alpha_{\text{chart}}$. Difficulties arise in checking the hopper outlet dimensions (as affected by the flow factor) because values of $\alpha$ not lying on the mass flow limit in the case of plane flow, or, $3^\circ$ less than the limit for axisymmetric hoppers, relate to flow factors not displayed in Figures 4.8 or 4.9. Reference to the original Jenike flow factor charts (Figures 4.1 and 4.2) indicate that the flow factor may be above or below that displayed in the alternative presentation, depending on the value of $\alpha$ used within the bounded mass flow region. It is recommended that for this exercise the Jenike charts be consulted because the complete flow factor variation with $\alpha$ is displayed for given values of $\phi$ and $\delta$.

4.4 ILLUSTRATIVE EXAMPLE

To demonstrate the use of these new design charts, the geometry
of a mass flow hopper with a plane flow outlet for an ROM coal storage will be determined. The measured flow properties of the coal are presented as a function of the major consolidation stress $\sigma_1$ in Figure 4.10 and in equation form in Table 4.1.

Two characteristics, typical of moist cohesive bulk solids such as coal, are depicted in Figure 4.10. These are the reductions of $\delta$ and $\phi$ (for some wall materials) to limiting values with increasing $\sigma_1$. The variation of the wall friction angle may be due to either convex upward wall yield locus and/or the tendency of the bulk solid to adhere to the wall lining material at low values of normal stress.

A portion of Figure 4.9 is presented in Figure 4.11, which displays $\alpha$ contours at $1^\circ$ increments and the flow factor contours at 0.01 intervals. As previously stated, an iterative procedure must be used to determine the critical hopper geometry if either $\delta$ or $\phi$ vary with $\sigma_1$. Essentially, the procedure suggested by Jenike [3] will be applied, first determining the critical flow factor value, noting the respective $\alpha$ value and then applying the flow factor value to Equation 1.2 to yield the hopper outlet dimension. The procedure is deemed to have converged to the critical values when little change results in $\sigma_1$ and $\delta$ from successive iterations.

Consider the determination of the hopper geometry under instantaneous conditions with the UHMW polymer as the wall lining material. To start the procedure initially estimate $\delta = 60^\circ$. With $\phi = 23^\circ$ and constant, from Figure 4.11 point A yields a flow factor value of 1.111.

Applying the flow-no flow concept to the instantaneous flow function and the respective flow factors produces an initial value for $\sigma_1$ of 2.07 kPa.
Flow Property Equation

<table>
<thead>
<tr>
<th>Property</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous Flow Function</td>
<td>$\sigma_c = 0.32\sigma_i + 1.20$</td>
</tr>
<tr>
<td>Time Flow Function (2 Day)</td>
<td>$\sigma_{ct} = 0.35\sigma_i + 2.05$</td>
</tr>
<tr>
<td>Bulk Density Variation</td>
<td>$\rho = 850.74(\sigma_i / 5.925)^{0.069}$</td>
</tr>
</tbody>
</table>

Table 4.1: Flow Property Equations for Design Example.

![Graph](image)

Figure 4.10: Flow Properties of $\delta$ and $\phi$ for the Design Example.
Figure 4.11: Determination of the Hopper Geometry for the Design Example.
That is for the following equations:

flow function: \[ \sigma_c = 0.32\sigma_1 + 1.20 \]

flow factor: \[ \text{ff} = \frac{\sigma_c}{\sigma_1} = 1.111 \]

and at the critical design point, \( \sigma_1 = \sigma_c \). Then,

\[ \sigma_c = \sigma_1 = \frac{\sigma_1}{1.111} \]

and

\[ \frac{\sigma_1}{1.111} = 0.32\sigma_1 + 1.20 \]

Solving for \( \sigma_1 \),

\[ \sigma_1(\frac{1}{1.111} - 0.32) = 1.20 \]

and hence

\[ \sigma_1 = 2.07 \text{ kPa.} \]

Reference to the \( \delta \) variation depicted in Figure 4.10 for this value of \( \sigma_1 \) yields an updated value of \( \delta \) of 64.5\(^\circ\).

The subsequent values for each iteration in converging to the critical values are presented in Table 4.2. For the values of \( \delta \) (64.6\(^\circ\)) and \( \phi \) (23.1\(^\circ\)), the flow factor and \( \alpha \) can be read from Figure 4.10 as 1.079 and 30.3 (say 30.5\(^\circ\)) respectively. As indicated in the above table, convergence occurs relatively fast. Substitution of the relevant values into Equation 1.2 allows the critical outlet dimension to be determined. From the graphical presentation of \( H(\alpha) \) [3] (or alternatively Equation 5.2),

\[ H(\alpha) = H(\alpha = 30.5) = 1.15 \]

and

\[ \rho = \rho (\sigma_1 = 1.98) = 788.1 \text{ kg/m}^3 \]

and hence \( B = 273\text{mm} \) (say 275mm). The critical hopper geometry parameters would then be detailed as \( \alpha = 30.5\(^\circ\) \) and \( B = 275\text{mm} \).

The procedure becomes further complicated when considering a
### Table 4.2: Convergence to the Critical Value for the Design Example, with Constant Wall Friction.

<table>
<thead>
<tr>
<th>Iteration No.</th>
<th>δ (°)</th>
<th>ff</th>
<th>σ₁ (kPa)</th>
<th>φ (°)</th>
<th>Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>assume 60</td>
<td>1.111</td>
<td>2.07</td>
<td>23.0</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>64.5</td>
<td>1.080</td>
<td>1.98</td>
<td>23.0</td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>64.6</td>
<td>1.079</td>
<td>1.98</td>
<td>23.0</td>
<td>C</td>
</tr>
</tbody>
</table>

### Table 4.3: Convergence to the Critical Value for the Design Example, with Variable Wall Friction.

<table>
<thead>
<tr>
<th>Iteration No.</th>
<th>δ (°)</th>
<th>ff</th>
<th>σ₁ (kPa)</th>
<th>φ (°)</th>
<th>Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>assume 60</td>
<td>1.115</td>
<td>3.75</td>
<td>assume 20</td>
<td>D</td>
</tr>
<tr>
<td>2</td>
<td>62.3</td>
<td>1.098</td>
<td>3.66</td>
<td>18.7</td>
<td>E</td>
</tr>
<tr>
<td>3</td>
<td>62.4</td>
<td>1.097</td>
<td>3.65</td>
<td>18.9</td>
<td>T</td>
</tr>
</tbody>
</table>

Table 4.2: Convergence to the Critical Value for the Design Example, with Constant Wall Friction.

Table 4.3: Convergence to the Critical Value for the Design Example, with Variable Wall Friction.
lining material that has a variable kinematic angle of wall friction. To illustrate the design procedure when both $\phi$ and $\delta$ vary with $\sigma_1$, the critical geometry parameters will be determined for time storage conditions (2 days at rest), using stainless steel as the wall lining material. In a similar fashion to the previous example, values of $\delta$ and $\phi$ must be assumed to obtain an initial flow factor value. Assuming $\delta = 60^\circ$ and $\phi = 20^\circ$, the iteration values are presented in Table 4.3:

For the final values of flow factor $ff = 1.097$ and $\alpha = 35.5^\circ$, the critical outlet dimension can be determined as 485 mm, with $H(\alpha) = 1.18$ and $\rho = 822.5$ kg/m$^3$.

The variation of $\phi$ with $\sigma_1$ can be utilised in mass flow hopper design by allowing larger wall slopes for outlet dimensions greater than the critical value determined in relation to particular instantaneous or time flow functions. The hopper wall slope may be increased due to the reduction on wall friction which occurs from the increased values of $\sigma_1$ resulting from increased outlet dimensions. The variation of $\alpha$ with B can be determined by incrementing $\sigma_1$ above the critical value, calculating the respective values of $\phi$ and $\delta$ and, from Figure 4.11, reading the respective values of $\alpha$ and the flow factor. Knowing the flow factor and the value of $\alpha$ allows the outlet dimensions to be calculated.

The variation of $\delta$ and $\phi$ for a range of $\sigma_1$ has been presented as a curve in Figure 4.11. This curve is unique to the particular variations of $\phi$ and $\delta$ with $\sigma_1$ and, as indicated, the critical design points for instantaneous (point I) and time storage (point T) conditions lie on this locus.
<table>
<thead>
<tr>
<th>$\sigma_1$ (kPa)</th>
<th>$\delta$ (°)</th>
<th>$\phi$ (°)</th>
<th>ff</th>
<th>$\alpha$ (°)</th>
<th>B (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.98</td>
<td>64.6</td>
<td>21.7</td>
<td>1.080</td>
<td>31.8</td>
<td>275</td>
</tr>
<tr>
<td>2.50</td>
<td>63.9</td>
<td>20.4</td>
<td>1.086</td>
<td>33.4</td>
<td>342</td>
</tr>
<tr>
<td>3.00</td>
<td>63.2</td>
<td>19.6</td>
<td>1.091</td>
<td>34.5</td>
<td>405</td>
</tr>
<tr>
<td>4.00</td>
<td>62.0</td>
<td>18.6</td>
<td>1.100</td>
<td>35.8</td>
<td>528</td>
</tr>
<tr>
<td>5.00</td>
<td>61.0</td>
<td>18.0</td>
<td>1.109</td>
<td>36.6</td>
<td>647</td>
</tr>
<tr>
<td>8.50</td>
<td>5.81</td>
<td>17.0</td>
<td>1.134</td>
<td>38.0</td>
<td>1042</td>
</tr>
<tr>
<td>10.00</td>
<td>57.1</td>
<td>16.8</td>
<td>1.143</td>
<td>38.3</td>
<td>1204</td>
</tr>
<tr>
<td>15.00</td>
<td>54.7</td>
<td>16.4</td>
<td>1.168</td>
<td>39.0</td>
<td>1724</td>
</tr>
</tbody>
</table>

Table 4.4: Variariation of Outlet Dimension and Hopper Wall Slope with Increasing Major Consolidation Stress for the Design Example.
Table 4.4 summarises the variation of $\phi$ and $\delta$ with $\sigma_1$ and the resulting variation of $\alpha$ with $B$ for stainless steel. It can be seen that for plane flow hopper outlets in the region of 1 metre width, wall slopes of $38^0$ could be utilised. This design data can also be applied to increasing the hopper wall slope in a stepwise fashion at intermediate levels above the hopper outlet. As the effective width of the hopper increases due to divergence of the walls, the wall slope can be increased in accordance with the above variation. This technique can prove useful in design applications that have headroom and space constraints and also in determining the extent of hopper wall linings.

4.5 CONCLUDING REMARKS

The advantages resulting from this presentation over existing methods include:

- The ability to obtain an overall assessment of the variation of the design parameters of $\alpha$ and flow factor along the limits of mass flow chosen for design purposes.
- All the relevant design data required for hopper geometry determination are presented on one chart (for either axisymmetric or plane flow hoppers), which reduces the amount of parameter interpolation required.
- A characteristic curve can be plotted on the chart presentation representing the variation of $\phi$ and $\delta$ with increasing $\sigma_1$. The critical values of $\phi$ and $\delta$ for instantaneous and time storage conditions lie on this curve. The respective values of $\alpha$ and flow factor as specified by the curve can be utilised to present the variation of $\alpha$ for values of $B$ greater than the critical.
- The data mesh used to determine the contour positions on the chart can be applied to compile a hopper design computer
program using linear interpolation techniques (rather than the solution of differential equations) to determine the required design parameters.

These hopper design parameter charts have recently been incorporated into the new *Draft Code Practice for the Design of Silos and Bins* prepared by the British Materials Handling Board. [44].
CHAPTER 5

GRAPHICAL DETERMINATION OF THE MASS FLOW HOPPER GEOMETRY PARAMETERS

5.1 INTRODUCTION

The determination of the geometry of mass flow hoppers is based on the design data of the critical hopper outlet dimension B and the maximum values of wall slope $\alpha$, for both instantaneous and time storage conditions, and graphs of the variation of hopper wall slope with outlet dimension for each wall material considered. This method of design data presentation, particularly regarding the $\alpha$ versus B charts has a number of disadvantages.

Firstly, to produce the $\alpha$ versus B graphs without the aid of computers can be a complicated and tedious task, requiring reference to the relevant flow properties and hopper flow factor charts. To employ computer techniques, on the other hand, requires a powerful computer and the necessary algorithms and mathematical support code to generate flow factors from first principles. As presented by Arnold et al. [45] and Moore et al. [46] the development of such programs is an involved and complex task. (Chapter 7 discusses the development of computer software for flow property processing and bin design).

A second aspect of the current hopper geometry data presentation methods is the failure to relate the critical hopper geometry to the experimental flow properties, or to the design stress values acting at the hopper outlet. It would be helpful, particularly in the design for difficult cohesive bulk materials, to allow an insight into the design procedure and an appreciation of the sensitivity of results due to flow property variations.
A further consideration is the difficulty in relating hopper design parameters with experimentally determined flow properties when applying computer techniques to process the flow property data and determine the critical hopper geometry parameters. The use of computers can cause the design engineer to lose sight of the basic flow property data in its application to hopper design. In the computer procedures, flow properties such as the flow function, are represented by curve fitting an assumed empirical function form to several discrete data points. This can lead to significant errors if the fitted curve is not an accurate representation of the complete flow property. Using the current presentation of design data the following useful trends and relations cannot be easily visualised:-

• the sensitivity of changes in the flow function position on the minimum opening dimension. This is important for low values of $\sigma_1$ removed from the experimental data points,
• the correlation of the hopper wall slope with the angle of wall friction,
• the relation between hopper outlet dimension and $\sigma_1$.

To eliminate some of the present difficulties, an alternative graphical method of design data presentation in the form of design nomograms has been developed which clearly shows the relation between the hopper geometry parameters and the experimentally determined flow properties. The graphical design nomograms represent a compact, rapid method of manually determining the mass flow hopper geometry parameters.

This chapter details the determination of mass flow hopper geometry parameters using the graphical design nomograms, which were developed by combining the concepts and graphical formats introduced from the alternative presentation of the hopper design parameters (Chapter
4) [47] and the novel method of presenting mass flow hopper geometry parameters developed by Moore and Arnold [48].

5.2 NOMOGRAMS FOR MASS FLOW HOPPER DESIGN

Design nomograms or graphical worksheets have been developed for axisymmetric and plane flow hopper design, and are presented in Figures 5.1 and 5.2 respectively. Figures 5.3 and 5.4 present alignment nomograms for the calculation of the critical outlet dimension B for axisymmetric and plane flow hoppers respectively.

Referring to Figures 5.1 and 5.2, the layout of the nomograms essentially allows the presentation of the bulk solid flow properties (as a function of $\sigma_1$) on the left side and the alternative hopper design parameter chart ($f_f$ and $\alpha$) on the right. To use the nomogram, the bulk solid flow properties are first drawn against the respective axes. Note the $\phi$ versus $\sigma_1$ variation determination depends on the wall yield locus and the effective angle of friction, and, involves Mohr circle stress analysis as reported in [45] (refer to Appendix I). A separate nomogram or worksheet is prepared for each hopper wall material that is considered.

The first step in operating the nomogram is generating the 'flow factor locus'. An arbitrary $\sigma_1$ value is selected and by projecting this value vertically the corresponding values of $\phi$ and $\delta$ are found. These two friction values are then projected onto the hopper design parameter chart and the corresponding values of $f_f$ and $\alpha$ read from the intersection point. In the lower left work space, using the flow factor scale, the intersection between the $f_f$ and $\sigma_1$ values is plotted. This is one point on the flow factor locus.

The flow factor locus is the curve passing through the coordinates $(\sigma_1, \frac{f_f}{\tau_{HF}})$ displaying the variation of the flow factor with respective values of $\sigma_1$. 
Figure 5.1: Design Nomogram for Axisymmetric Mass Flow Hoppers.
Figure 5.2: Design Nomogram for Plane Flow Mass Flow Hoppers.
Figure 5.3: Alignment Nomogram for Calculation of Outlet Dimension, Axisymmetric Hoppers.
Figure 5.4: Alignment Nomogram for Calculation of Outlet Dimension, Plane Flow Hoppers.
This curve is unique to the particular bulk solid, being dependent only on the angle of wall friction, the effective angle of friction and the shape of the hopper outlet (axisymmetric or plane flow).

The flow factor locus does not usually pass through the origin, but begins at the first value of $\sigma_1$ that yields $\phi$ and $\delta$ for which a flow factor for mass flow can be determined. For wall materials displaying high levels of adhesion with the bulk solid this first value of $\sigma_1$ can be as high as 2.5 - 3.0 kPa. Note that if $\phi$ and $\delta$ for the bulk solid are constant, then the flow factor locus will be a straight line indicating a constant $ff$ (and $\delta$) for all values of $\sigma_1$.

The value of $\alpha$ (determined at the same time as $ff$) can be plotted against the $\sigma_1$ abscissa corresponding to the hopper wall slope scale provided.

The value of the hopper outlet dimension $B$ is determined from the alignment nomograms (Figures 5.3 and 5.4) which solve Equation 1.2, and include functional scales for $H(\alpha)$ (presented graphically in [3]). These nomograms could be deemed unnecessary with the common application of electronic calculators, particularly if the relations presented by Arnold et al. [4] for $H(\alpha)$ are utilised.

For axisymmetric hoppers:

$$H(\alpha) = \frac{(130 + \alpha)}{65}$$

(5.1)

and for plane flow hoppers:

$$H(\alpha) = \frac{(200 + \alpha)}{200}$$

(5.2)

where $\alpha$ is in degrees.

Referring to these figures, first, line (i) is drawn between the $p$ scale (for the relevant $p$ value corresponding to $\sigma_1$) and the $\alpha$ value. This provides an
intersection point on the reference line from which line (ii) is projected through the $\bar{\sigma}_1$ value and onto the critical arching dimension scale. The $\bar{\sigma}_1$ value is determined by projecting the flow factor - $\bar{\sigma}_1$ intersection point onto the $\sigma_1$ axis (in the lower left work space) or by solving $\bar{\sigma}_1 = \frac{\sigma_1}{f_f}$. The subsequent value of $B$ can then be plotted along the $\sigma_1$ abscissa corresponding to the critical arching dimension axis provided.

The above operations are repeated for a range of $\sigma_1$ values ranging from perhaps 1 kPa to 15 kPa to allow curves to be plotted providing the following parameter variations as a function of major consolidation stress, $\sigma_1$:

- the flow factor locus,
- the hopper wall slope, $\alpha$,
- the hopper outlet dimension, $B$.

The hopper geometry parameters for instantaneous and time storage consolidation conditions are determined by establishing the critical $\sigma_1$ value, where the appropriate flow function intersects with the flow factor locus. The critical values of $\alpha$ and $B$ can then be read from the respective plotted curves for the appropriate $\sigma_1$ value.

5.3 ILLUSTRATIVE EXAMPLE

A design example using the nomogram to determine the hopper geometry parameters for a plane flow slot outlet hopper storing black coal is provided in Figure 5.5. For convenience, Figure 5.6 provides an enlarged presentation of the lower left portion of Figure 5.5. The required flow properties have been plotted in the appropriate section on the left side of the graph.
MAJOR CONSOLIDATION STRESS, $\sigma_1 \text{ kPa}$

MAJOR STRESS IN ARCH, $\sigma_m \text{ kPa}$

HOPPER GEOMETRY FOR MASS FLOW
(PLANE FLOW)

Figure 5.5: Determination of the Plane Flow Hopper Geometry for the Design Example.
Figure 5.6: Determination of the Plane Flow Hopper Geometry for the Design Example (enlarged portion).
Selecting a value of $\sigma_1 = 5$ kPa to illustrate the procedure, projecting this value (line (a)) to the $\delta$ and $\phi$ flow properties, values of $61^\circ$ and $18^\circ$ respectively are found. These values are projected (lines (b) and (c)) onto the hopper design parameter chart and intersect at point 1, yielding values of $\text{ff} = 1.11$ and $\alpha = 37^\circ$. Drawing in the flow factor ray of $\text{ff} = 1.11$ determines intersection point 2 with $\sigma_1 = 5$ kPa. Point 3 for $\alpha = 37^\circ$ can also be plotted against the appropriate scale. Using the alignment nomogram, B is determined for the values: $\rho = 840$ kg/m$^3$, $\sigma_1 = \frac{\sigma_1}{\text{ff}} = \frac{5.0}{1.11} = 4.5$ and $\alpha = 37^\circ$. The value of $B = 650$ mm is found and plotted at point 4. This procedure has been repeated to generate the complete flow factor locus and the $\alpha$ and B variations.

The critical hopper geometry parameters for instantaneous and time consolidation conditions are determined from the intersection of the relevant flow function with the flow factor locus. For the critical $\sigma_1$ value found, the corresponding values of $\alpha$ and $B$ are noted.

Then, for instantaneous conditions:

Point 5, $\alpha = 32.5^\circ$, $B = 350$ mm

and for time storage conditions:

Point 6, $\alpha = 35.5^\circ$, $B = 540$ mm.

Often, the exact position of the flow function may not be known accurately because it generally results from drawing a line through three experimentally derived points from the instantaneous or time yield locus. The sensitivity of the $\alpha$ and B values to variations in the location of the flow function can be assessed easily.

For example, in Figure 5.6, it can be seen that changing the flow function to $\text{FF}_{T2}$ yields a new intersection, point 7, between the flow function and the flow factor locus. This intersection point defines a value of
\( \sigma_1 = 5.8 \text{ kPa} \) with consequent \( \alpha \) and \( B \) values of \( 37.5^\circ \) and 740 mm respectively.

This section of the worksheet indicates that flow functions may have different characteristics and yet still lead to similar critical hopper geometry parameters, for example, a flow function with high initial cohesion with a small gradient compared to a flow function with a low cohesion but steeply sloping.

Perhaps a more important feature that is highlighted by this presentation is the degree of influence \( \phi \) has on the hopper geometry. For many bulk solids, the outlet dimension of hoppers will exceed the critical value, (ie. Point 5, for instantaneous conditions). Thus the subsequent geometry need only follow the prediction of the \( \alpha \) versus \( \sigma_1 \) and \( B \) versus \( \sigma_1 \) curves, which are predominantly under the influence of the \( \phi \) variation.

This feature provides an effective method for the experienced designer to determine the hopper geometry parameters based on a reduced flow property testing program. Only the wall friction and compressibility tests are required, tests which are rapid and relatively straightforward compared to shear testing (note that the important wall friction parameter can be determined on any suitable Coulomb friction tester).

Based on experience, the effective angle of internal friction, \( \delta \), possible flow function positions and \( B \) can be estimated. The discussions of Chapter 4 have highlighted the limited sensitivity of \( \varphi \) and particularly \( \alpha \) to variations in \( \delta \). Thus the \( \alpha \) versus \( \sigma_1 \) and \( B \) versus \( \sigma_1 \) design curves can be generated and extremely useful hopper design information achieved.

The detailing of the hopper geometry as part of a bulk solids handling system often requires attention to such constraints as allowable head room, maximum lump size, feeder arrangements, proposed discharge
flow rates and economy of design for the required storage tonnage. The hopper wall slope and outlet dimension design curves allows the design engineer to confidently vary each parameter above the critical value to satisfy any constraints acting. For example, if the slot outlet width has to be constrained to some value above the critical, the hopper wall slope could be increased according to the design curves allowing a reduced hopper height and relief to possible headroom problems.

A further application of this presentation is the ability to optimise the selection of \( \alpha \) and \( B \) in regard to feeder loading. For example, utilising Reisner's theory [4] for the calculation of the flow load, the major consolidation pressure \( \sigma_1 \) at the hopper outlet is assumed to act vertically on the feeder. The value of \( \sigma_1 \) can be found by rearranging Equation 1.2:

\[
\sigma_1 = \frac{\gamma Bff}{H(\alpha)} \tag{5.3}
\]

and hence the total flow load, \( Q \), can be determined from Equation 5.4:

\[
Q = \sigma_1 A \tag{5.4}
\]

where \( A \) is the cross-sectional area of the hopper outlet. It would be straightforward to provide a additional graph of \( Q \) versus \( \sigma_1 \) (in a similar format to the other flow properties or design parameters), allowing a direct indication of the feeder flow loading with increase of the outlet dimension. Alternatively, \( Q \) could be conveniently calculated at point values of \( B \) as the current worksheet format clearly depicts the required \( B \) and \( \sigma_1 \) values.

5.4 CONCLUDING REMARKS

The design nomograms presented in this chapter provide a compact and accurate method for the manual calculation of the mass flow hopper geometry parameters. The presentation has advantages over
existing methods in that the relation between the flow properties and the hopper geometry is clearly illustrated, the hopper design parameter chart requires no interpolations and the sensitivity of geometry parameters may be examined in view of doubtful or dubious flow property variations.

The procedure described here also lends itself to computerisation, with computer graphics being used to produce the final design graphs. These aspects will be further developed in Chapter 7.
CHAPTER 6

STANDARDISED HOPPER GEOMETRY DESIGN GUIDELINES

6.1 INTRODUCTION

Review of the critical hopper geometry parameters presented in Table 3.1 and of the flow property values in Table 2.1, raises the feasibility of utilising standard design guidelines for the determination of the hopper geometry parameters of $\alpha$ and $B$ for mass flow. This is achieved by determining the expected ranges of $\alpha$ and $B$, dependent on the moisture content of the coal and secondly by analysing statistically determined flow properties allowing a reduced flow property testing procedure to be formulated.

Advantages of such a procedure include:

- Reduction of the amount of flow property testing required for the design of coal storage bins. For storage facilities that handle several different coals (eg. an export market coal loader) a relatively large amount of time and expense is required for flow property testing to identify the worst case bulk solid, to define the design criterion.

- Often coal storage and processing facilities are detailed without an appreciation of the principles of bulk storage and flow [18]. Utilisation of such guidelines would increase the awareness of industry and encourage a systematic approach to the design of coal storage facilities.

- Allow the accurate preparation of initial arrangement layouts of coal storage facilities early in the design process. This would be particularly useful for facilities for which no bulk samples exist,
such as new mine developments where only bore hole samples are available. This approach would highlight storage geometry constraints earlier, and also allow more accurate costing estimates to be prepared.

Several authors have conducted studies in this direction. ter Borg [31, 49] and Dau [32] have investigated the flow properties and subsequent mass flow hopper geometry parameters for large numbers of bulk solids for statistical application in the chemical industry. Figure 6.1 presents, for a survey of 500 bulk solids [31], the percentage of bins that would successfully operate in mass flow as a function of the hopper wall slope angle. As indicated, for axisymmetric hoppers with $\alpha_c = 30^\circ$, only 25% of installations would be expected to mass flow. However, silo designers and manufacturers of packaged and purpose-designed silos still regard this slope as sufficiently steep. Referring to the plane flow variation (which is increased from the axisymmetric case by $8^\circ - 10^\circ$, Schwedes [50]), for $\alpha_p = 30^\circ$, 50% of installations would be expected to operate in mass flow.

The second aspect of hopper design, the determination of the outlet dimension, has been investigated statistically by Sinkwitz [51] and Horn [52]. Sinkwitz attempted to apply a cohesive arch or bridge-forming probability to yield hopper outlet dimensions (with a success risk factor) smaller than the outlet dimensions determined by the Jenike method [3]. This approach aimed to reduce the amount of overdesign which has been indicated by several experimental studies, and recently discussed by Jenike [53].

6.2 TERMS OF REFERENCE

In developing this concept, the interaction of the coal (represented by the respective flow properties) and the operational characteristics of mass flow bins must be taken into account. The heterogeneous nature of black
Figure 6.1 Bulk Solids with Mass Flow as a Function of Hopper Wall Slope (ter Borg [31] and Schwedes[50]).
coal (physically and chemically) is well known, leading to variations in the flow properties of different coals and their relative flowability. Colijn and Vitunac [54] note that there appears to be no such product as a 'typical coal' or an 'average coal' in a similar manner to there being no 'typical soil' for soil mechanics to work with. For these reasons, the coal types applicable for this procedure are restricted to similar coals used in the test work. These coals could be defined as:

- Hard Black Coals.
- Bituminous to Semi-Anthracite Rank.
- Hardgrove Grindability Index : HGI < 60.
- Ash Content (non swelling clay) < 15%.
- Similar particle distributions as defined by the Rosin-Rammler Distribution Parameters.

The ash content has been specified in broad terms only. For those clay types that are known to lead to handling problems flow property testing will have to be undertaken and the traditional design approach employed. The Hardgrove Grindability has been specified to restrict coals to the harder and less friable coal types. The testwork has highlighted the increased storage problems due to the increased cohesive strength that occurs for friable coals, due to the increased fines content caused by degradation from repeated handling operations. Most coals tested in the program displayed similar particle distributions for the as received samples resulting from isotropic breakage and obeying the Rosin-Rammler Distribution. The Rosin-Rammler Distribution Parameters presented in Table 6.1 for the coals tested demonstrates this feature.

The moisture content of the coal was shown to be a significant parameter. For the coals from the Southern Coalfield the maximum outlet spans occurred for the moisture range of 10% - 15%. Coal samples below
Table 6.1 Comparison of the Rosin-Rammler Particle Distribution Parameters for Coals Tested (As Received Condition)

<table>
<thead>
<tr>
<th>Colliery</th>
<th>Rosin-Rammler Distribution Parameters</th>
<th>X</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coalcliff</td>
<td></td>
<td>4.77</td>
<td>0.811</td>
</tr>
<tr>
<td>South Bulli</td>
<td></td>
<td>4.98</td>
<td>0.880</td>
</tr>
<tr>
<td>Huntley</td>
<td></td>
<td>4.46</td>
<td>0.790</td>
</tr>
<tr>
<td>Metropolitan</td>
<td></td>
<td>3.27</td>
<td>0.713</td>
</tr>
<tr>
<td>Appin</td>
<td></td>
<td>5.73</td>
<td>0.829</td>
</tr>
<tr>
<td>Westcliff (ROM)</td>
<td></td>
<td>7.07</td>
<td>0.779</td>
</tr>
</tbody>
</table>
these levels will be less cohesive and thus more free flowing, while coals above the 15% level (and possessing the approximate particle distribution found in the testing program) would be close to the saturated moisture content. Moisture contents higher than 15% could also indicate high fines contents or expansive clays present within the ash content.

The design procedure in determining the hopper geometry parameters aims to achieve a reasonable compromise between such technical aspects as headroom and capacity requirements, allowable values of hopper wall slope for various wall lining materials, outlet dimension, type and size of feeder and feeder loads. There are three basic shapes of mass flow hoppers, namely, axisymmetric, plane flow and transition (a combination of a plane flow hopper with conical end walls), as depicted in Figure 1.2.

Considering the design and operational merits of the various mass flow hoppers, the following aspects are significant:

- Axisymmetric hoppers operate with a distinct mass / funnel flow boundary (linking $\alpha$ with $\phi$ and $\delta$) as depicted in Figure 1.3. Plane flow hoppers, in contrast, have a less distinct operational boundary between mass flow and funnel flow. To this effect Jenike [3] states that the plane flow hopper slope may be increased up to $5^\circ$ above the design recommendation if the cylinder/hopper transition is generously radiused rather than meeting at a distinct intersection.

- As previously stated, the plane flow hopper slope $\alpha_p$ is generally $9^\circ - 11^\circ$ greater than the slope required for axisymmetric hoppers. Thus plane flow hoppers can offer a more economical design in terms of height [55].
• A limitation of plane flow hoppers is the requirement for long slot outlets ($L > 3B$). This restricts, to some degree, the type of feeder used. More particularly, care must be taken to ensure the outlet is completely live, with the bulk solid being withdrawn over the complete outlet area. If this does not occur then funnel flow will develop within the stagnant contents of the bin.

• Pyramidal hoppers are limited because of the in flowing valleys between each hopper face. These valleys present high friction regions to bulk solid flow and lead to material hang ups. Designers will find specifying the hopper valley angle equal to $\alpha_c$ [3] will often lead to impractical hopper proportions. For this reason it is recommended that only axisymmetric hoppers of conical form be considered.

The testwork considered three wall lining materials, rusty mild steel, 304-2B stainless steel and Pactene. For the development of these guidelines only stainless steel will be considered since its use is well proven in the coal industry, it offers low wall friction angles, a stable surface finish after long periods of contact with moist coal and is a reasonably wear resistant material. Rusty mild steel was discounted due to its high $\phi$ values and the inherent surface deterioration that occurs from contact with wet coal by rusting. The Pactene has $\phi$ values intermediate to stainless steel and rusty mild steel, but may not have the wear resistance required, particularly for ROM coal storage bins. The flammability and electrostatic properties of the Pactene also make it unacceptable for underground applications where spontaneous combustion or dust/gas explosions are possible.
Design engineers often do not appreciate the relatively steep hopper wall slopes and large outlet widths required for mass flow. This is certainly applicable to past coal bin designs. To highlight expected ranges for the $\alpha$ and $B$ parameters, the respective values determined from the -2.36mm and -4.00mm test samples have been analysed.

It is recognised that the sample set is relatively small, and for this reason, the Student's $t$ Distribution has been utilised. This approach allows the mean of the sample set to be linked to the mean of a normally distributed population, in this case the geometry parameters of $\alpha$ and $B$. The confidence interval based on this distribution provides a range in which the mean would be expected, with a specified probability.

The values presented in Table 6.2 display the mean value with a confidence interval of 90%. Note that increasing the confidence level to say, 95% often is of little practical value because this has the effect of increasing the length of the interval.

These tabulated values are intended to provide a guide to typical geometry values, particularly during the layout phases of a design process. The effect of the moisture content of the coal is well demonstrated, particularly with the lower hopper slopes allowable for coals of 6% moisture content, and the increasing trend of outlet dimensions for higher moisture content levels (for instantaneous and time storage conditions). It should be noted that the above tabulated values have been rounded off, in the case of outlet dimensions to the nearest multiple of 5mm, and for wall slopes to the nearest 0.5° above.
<table>
<thead>
<tr>
<th>Hopper Geometry Parameter</th>
<th>Sample Set n</th>
<th>Mean Value (within 90% Confidence Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% $\alpha_c (\circ)$</td>
<td>7</td>
<td>$14.4 &lt; 16.5 &lt; 18.5$</td>
</tr>
<tr>
<td>$\alpha_p (\circ)$</td>
<td>7</td>
<td>$23.5 &lt; 25.5 &lt; 27.5$</td>
</tr>
<tr>
<td>$B_c (\text{mm})$</td>
<td>7</td>
<td>$645 &lt; 735 &lt; 825$</td>
</tr>
<tr>
<td>$B_{cl} (\text{mm})$</td>
<td>5</td>
<td>$635 &lt; 825 &lt; 1015$</td>
</tr>
<tr>
<td>$B_p (\text{mm})$</td>
<td>7</td>
<td>$315 &lt; 350 &lt; 385$</td>
</tr>
<tr>
<td>$B_{pt} (\text{mm})$</td>
<td>5</td>
<td>$375 &lt; 420 &lt; 465$</td>
</tr>
<tr>
<td>10% $\alpha_c (\circ)$</td>
<td>13</td>
<td>$20.5 &lt; 21.5 &lt; 22.5$</td>
</tr>
<tr>
<td>$\alpha_p (\circ)$</td>
<td>13</td>
<td>$30.0 &lt; 31.0 &lt; 32.0$</td>
</tr>
<tr>
<td>$B_c (\text{mm})$</td>
<td>13</td>
<td>$950 &lt; 1060 &lt; 1170$</td>
</tr>
<tr>
<td>$B_{cl} (\text{mm})$</td>
<td>11</td>
<td>$1330 &lt; 1520 &lt; 1710$</td>
</tr>
<tr>
<td>$B_p (\text{mm})$</td>
<td>13</td>
<td>$435 &lt; 485 &lt; 535$</td>
</tr>
<tr>
<td>$B_{pt} (\text{mm})$</td>
<td>11</td>
<td>$590 &lt; 690 &lt; 785$</td>
</tr>
<tr>
<td>15% $\alpha_c (\circ)$</td>
<td>14</td>
<td>$21.5 &lt; 22.5 &lt; 23.5$</td>
</tr>
<tr>
<td>$\alpha_p (\circ)$</td>
<td>14</td>
<td>$31.5 &lt; 33.0 &lt; 34.5$</td>
</tr>
<tr>
<td>$B_c (\text{mm})$</td>
<td>14</td>
<td>$980 &lt; 1100 &lt; 1220$</td>
</tr>
<tr>
<td>$B_{cl} (\text{mm})$</td>
<td>13</td>
<td>$1265 &lt; 1495 &lt; 1725$</td>
</tr>
<tr>
<td>$B_p (\text{mm})$</td>
<td>14</td>
<td>$400 &lt; 520 &lt; 580$</td>
</tr>
<tr>
<td>$B_{pt} (\text{mm})$</td>
<td>13</td>
<td>$595 &lt; 695 &lt; 795$</td>
</tr>
</tbody>
</table>

Table 6.2: Mean Values of Mass Flow Hopper Geometry Parameters, Within a 90% Confidence Interval, for Coals Tested at Various Moisture Contents.
6.4 CONSIDERATION OF THE FLOW PROPERTIES

The ability to characterise the flow properties of moist black coal would have significant benefits in reducing flow property testing and allow direct hopper design based on the material physical properties. The work of Schubert and Tomas [56,57] has pursued this direction over several years. They have successfully determined mathematical models which allow the calculation of the flow function on the basis of the mean particle size, the surface tension of the liquid, the solid and liquid bulk densities and the moisture content. Their studies have, however, considered only fine powders with particle distributions in the range of 40-500 µm, and fails in the application to large particle distributions typical of coal.

Reviewing the flow properties relevant to the determination of the hopper design parameters, the values corresponding to the critical design value of $\sigma_1$ is of most significance. Accordingly, the flow properties determined for the -2.36mm test samples (presented in Appendix C to H), have been collated and presented in Figures 6.2 through 6.7. These figures present, for axisymmetric and plane flow hopper design, the variation of the flow property ($\sigma_c$, $\phi_{304-2B}$, and $\rho$) mean value with a range of two standard deviations (ie. $\bar{x} - \sigma < \bar{x} < \bar{x} + \sigma$) for 6, 10 and 15% moisture contents. These figures clearly display the trend or characteristic form of each flow property. This will be significant later in the discussion, particularly when considering the flow function. The range of critical $\sigma_1$ applicable for each moisture content and hopper type has been determined by an iterative procedure based on the alternative flow factor charts (Figures 4.8 and 4.9) and the respective variations of $\phi$ and $\delta$. The range of flow factor values determined for each moisture content and hopper type is tabulated in Table 6.3.
Figure 6.2  Range of Flow Property Values for 6% Moist Coal Applicable to Axisymmetric Hopper Design.
Figure 6.3  Range of Flow Property Values for 6% Moist Coal Applicable to Plane Flow Hopper Design.
Figure 6.4  Range of Flow Property Values for 10% Moist Coal Applicable to Axisymmetric Hopper Design.
Figure 6.5  Range of Flow Property Values for 10% Moist
Coal to Plane Flow Hopper Design.
Figure 6.6 Range of Flow Property Values for 15% Moist Coal Applicable to Axisymmetric Hopper Design.
Figure 6.7  Range of Flow Property Values for 15% Moist Coal Applicable to Plane Flow Hopper Design.
<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Flow Factor Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Axisymmetric</td>
</tr>
<tr>
<td>6%</td>
<td>1.11 &lt; ff &lt; 1.27</td>
</tr>
<tr>
<td>10%</td>
<td>1.15 &lt; ff &lt; 1.25</td>
</tr>
<tr>
<td>15%</td>
<td>1.15 &lt; ff &lt; 1.26</td>
</tr>
</tbody>
</table>

Table 6.3: Range of Flow Factor Values at the Critical Design Point for Axisymmetric and Plane Flow Hoppers at Various Moisture Contents.
Comparison of the flow factor ranges indicates similar values for both hopper types, with the axisymmetric case approximately 0.1 larger than the plane flow value. The respective flow factor range for each case has been used to graphically determine the critical $\sigma_1$ range from the intersection with the flow function range. As indicated by the double hatched region in Figure 6.2 to 6.7, the critical $\sigma_1$ exists in a narrow band.

Graphically projecting the minimum and maximum $\sigma_1$ values onto the other flow properties allows the range of $\phi$, $\delta$ and $\rho$ to be defined. Comparison between Figures 6.2 and 6.7 show that for the same moisture content, the axisymmetric case has lower $\delta$ and $\phi$ values due to the slightly higher flow factor leading to higher values of $\sigma_1$. For increasing moisture content, larger critical $\sigma_1$ values are evident due to the intersection of the stronger flow functions with the relevant flow factors. The trend of larger $\sigma_1$ values also leads to lower $\phi$ values applicable for the 304-2B stainless steel.

An insight is gained into the variation of the hopper design parameters ($ff$ and $\alpha$) by referring to Figures 6.8 to 6.9. These figures represent an enlarged portion of the alternative hopper design parameter charts onto which the values of $\phi$ and $\delta$ from the critical $\sigma_1$ range determined in Figures 6.2 to 6.7 have been mapped. The curve within each crosshatched region represents the variation of the mean values of $\delta$ and $\phi$, as detailed in Figure 6.2 to 6.7.

Figure 6.8 (for axisymmetric hoppers) indicates that the flow factor value is relatively insensitive to the sample moisture because the inclination of the flow factor contours correspond to the trend of the enclosed areas representing increasing moisture content. This observation is not applicable to the plane flow case, Figure 6.9, because the flow factor contours are approximately vertical. Both Figure 6.8 and 6.9 emphasise that
Figure 6.8 Variation of $\delta$ and $\phi_{304-2B\,SS}$ for Moist Coal (at Various Moisture Contents) Mapped onto the Alternative Axisymmetric Hopper Design Parameter Chart.
Figure 6.9 Variation of $\delta$ and $\phi_{304-2BSS}$ for Moist Coal (at Various Moisture Contents) Mapped onto the Alternative Plane Flow Hopper Design Parameter Chart.
for both axisymmetric and plane flow hoppers, the hopper wall slope is
directly proportional to $\phi$ and quite insensitive to $\delta$, for $\delta: 50^\circ < \delta < 70^\circ$.

Reviewing the trends presented by the figures in this chapter it is
proposed that the flow property testing of black coals for mass flow hopper
design can be significantly reduced without compromising the success and
reliability of the design. This can be achieved by utilising the charted values
(Figures 6.2 to 6.7) for the properties that have little influence on $\alpha$ and $B$
and testing those flow properties which have a significant effect. To expand
this hypothesis, first consider the determination of $\alpha$ and $B$. As previously
stated the outlet dimension is given by:

$$B = \frac{\bar{\sigma}_1 H(\alpha)}{\rho g} = \frac{\bar{\sigma}_1 H(\alpha)}{(\frac{T}{H}) \rho g} \quad (1.2, \text{repeated})$$

Rearranging and substituting Equations 5.5 and 5.6 for $H(\alpha)$, for
axisymmetric hoppers:

$$B = \frac{\bar{\sigma}_1 (\alpha + 130)}{\rho \times 65} = \frac{\bar{\sigma}_1 (130+\alpha)}{637.65 \rho} \quad (6.1)$$

and for plane flow hoppers:

$$B = \frac{\bar{\sigma}_1 (\alpha + 200)}{\rho \times 200} = \frac{\bar{\sigma}_1 (\alpha+200)}{1962 \rho} \quad (6.2)$$

Thus the primary variables of the above equations are $\bar{\sigma}_1$, $\rho$ and $\alpha$.
An estimate of $B$ can be determined by considering each of these variables.
The value of $\bar{\sigma}_1$ is determined from the intersection between the flow
function and the relevant flow factor. As presented in Figures 6.2 to 6.7 for
various moisture contents and hopper types, the flow factor value range is
quite small, with a variation of approximately 0.1 for both axisymmetric and
plane flow outlets. However, considering the intersection with the range of
flow functions ($\bar{x} - \sigma < \bar{x} + \sigma$) the range of $\bar{\sigma}_1$ is approximately 1.5 to 2 kPa.
This variation is obviously too large to utilise in the estimation of $B$. 
The range of \( \sigma_1 \) can be reduced to an acceptable level by experimentally determining one coordinate \((\sigma_1, \sigma_c)\) of the flow function of the bulk solid under consideration, such that \( \sigma_1 \) is positioned close to, or within the \( \sigma_1 \) range of the double hatched intersection region for the relevant moisture contents depicted in Figures 6.2 to 6.7. The flow function can then be estimated, passing through \((\sigma_1, \sigma_c)\) and with the slope of the mean flow function. The value of \( \sigma_1 \) can then be determined from the intersection between the estimated flow function and the relevant flow factor range. The range \( \sigma_1 \) is given by the vertical difference of the intersections with the minimum and maximum flow factors, and is normally less than 0.25 kPa.

Utilisation of this approach, for black coals, allows the reduction of the instantaneous yield loci test from three consolidation levels to one. However, this alternative procedure, requires that the single yield locus \( \sigma_1 \) be positioned close to the required \( \sigma_1 \) range, to minimise the error from utilising the mean flow function slope in determining the intersection with the relevant flow factor range. The determination of the consolidation level for the single yield locus can be awkward due to the following aspects:

- determination of the required consolidation level for the yield test due to the indirect method \( \sigma_1 \) is determined, from the Mohr stress circle passing through the coordinates \((V,S)\) and tangent to the yield locus.
- the low values of \( \sigma_1 \) required. This is certainly the case for the 6% moisture coals, and may require the use of aluminium shear cells in preference to stainless steel, and coordinate levels of 2lb rather than the common lowest level of 3lb.

Values of \( \sigma_1 \) required to provide maximum confidence should be within the following ranges:
• 6%, $\sigma_1 : 1.5 < \sigma_1 < 3.0 \text{ kPa}$
• 10%, $\sigma_1 : 3.0 < \sigma_1 < 5.0 \text{ kPa}$
• 15%, $\sigma_1 : 3.5 < \sigma_1 < 6.0 \text{ kPa}$

For coals of different moisture contents to those presented, the slope of the estimated flow function should be interpolated between the trends of the known variations of 6%, 10% or 15% moisture content. This alternative approach can also be used for the estimation of the hopper outlet dimension for time consolidation at rest conditions. In a similar manner to the instantaneous flow function, a single time yield locus would be tested to provide one coordinate ($\sigma_1, \sigma_{ct}$) allowing the position of the time flow function to be estimated. While no graphical trends for the time flow function are provided, it is considered that sufficiently accurate values of $\sigma_1$ can be achieved using the slope of the respective mean instantaneous flow function.

The intersection between the estimated flow function and the flow factor range provides the range of $\sigma_1$ for the critical design point. This value allows the range of bulk density to be found and utilised. As indicated in Equation 6.1, an upper bound value of bulk density provides a conservative calculation of the hopper outlet dimension.

The remaining parameter, $\alpha$, influences Equation 6.1 to a minor degree through the $H(\alpha)$ term. The significant influence of wall friction on the determination of $\alpha$ has previously been highlighted. For this reason, and the importance of correct selection of $\alpha$ to achieve mass flow, experimental wall friction tests are considered mandatory. The determination of $\phi$ from the wall yield locus, although involving $\delta$, has a minor influence and a point value of $\delta$ estimated from Figure 6.2 to 6.7 would be adequate. The effect of $\delta$ is only of primary consideration in determining the minimum $\sigma_1$, for which the solution of $\phi_{\text{maximum}}$ can be
found. The determination of $\alpha$ from Figures 6.8 and 6.9, is straightforward based on $\phi$ (at the particular $\sigma_i$ estimated). On finding $\alpha$, Equation 6.2 and 6.3 (for axisymmetric or plane flow hoppers respectively), can be determined to yield estimates of the hopper outlet width.

The variation of $\phi$ is also of primary concern in determining the hopper geometry parameters for designs when the outlet dimension is greater than the critical. This is particularly the case for wall materials that display a reduction in $\phi$ with increasing $\sigma_i$. The variation of allowable hopper slope with outlet dimension can be determined by incrementing $\sigma_i$ and using the method described in Chapter 5.

6.5 CONCLUDING REMARKS

This chapter details the development of guidelines based on two approaches for the design of mass flow hoppers storing hard black coal. The first considers the expected values of $\alpha$ and $B$ represented by the mean of each parameter within a 90% confidence interval. The values were determined by analysing the hopper geometry parameter values determined from the flow property testing program, by the Student’s $t$ Distribution. The values of $\alpha$ and $B$ provide the design engineer with parameters which can be utilised at the layout stage, or when reviewing existing hopper designs. The expected values highlight the steeper hopper wall slopes required for coal at 6% moisture content and the larger outlet dimensions required for the 10% and 15% moist coals. For the design of facilities where the coal handled can have a range of moisture contents, this feature should be recognised.

The second approach involved the development of a reduced flow property testing program to determine/confirm those properties which exert significant influence on the values of $\alpha$ and $B$, while for those properties of less significance the expected values can be estimated from
charts. This approach stems from an analysis of the critical region of mass flow hopper design, involving the flow properties of $\sigma_c$, $\delta$, $\phi_{304-2B}$ and the relevant flow factor. The range of values for each flow property and the design parameters $\alpha$ and $\eta$ have been presented graphically for coal at 6, 10 and 15% moisture content.

The influence of wall friction for the determination of $\alpha$ is most significant. It is considered that the experimental wall friction test is mandatory in achieving reliable mass flow hopper design. Even for those situations where the outlet span is known from experience (or from shear testing) the achievement of mass flow operation rather than the ratholing characteristic of funnel flow is strongly dependent on the correct selection of $\alpha$, based on $\phi$. 
CHAPTER 7
APPLICATION OF COMPUTER AIDED DESIGN TECHNIQUES

7.1 INTRODUCTION

The use of digital computers as a processing aid applied to bulk materials handling has been recognised for some time, for example, the work of Stainforth et al. [58], Budalli [59] and Eelkman Rooda [60].

From the initial work of Martin [61] and Dwight [62], (undergraduate thesis topics, The University of Wollongong, supervised by Dr. A.G. McLean), two computer programs have been developed that follow the bin design procedure highlighted in Chapter 1.1. The first program, FP, deals with the flow properties of the tested bulk solid, processing the experimentally determined data and presenting the flow properties graphically and by empirical equations. The second program, BD, determines the mass flow hopper geometry parameters, at critical conditions and calculates the design chart of variation of hopper slope with increasing outlet dimension. The two programs are linked, in that the empirical flow property equations determined by the first program are used as the data input into the hopper design program.

Development of the programs has incorporated two important features.

- A high degree of operator interactive control. This allows a greater flexibility and freedom in selecting the required program option and on completion returning the operator to the main or root menu for the next selection.
The utilisation of high resolution graphics which has brought advantages in providing a convenient method of checking experimental data, checking and accepting experimental curve regressions and interpreting hopper design graphs.

The software was initially developed within the The University of Wollongong Computer System environment. This is a time-share system based on a UNIVAC 1100/80 mainframe computer, with FORTRAN as the primary programming language. The version of FORTRAN used is SPERRY-UNIVAC FORTRAN 77 (conforming to ANSI Standard X3.9-1978). While these programs have been developed specifically for the University system, using on-line packages such as the PLOT PACKAGE [63] and IMSL [64] their philosophy and program logic is applicable generally.

It has been recognised for some time that access to these programs was limited due to program operation only being available on the mainframe system. To allow wider exposure, particularly in view of the widespread use of powerful engineering design microcomputers, both programs have been transferred to a microcomputer design system within the Department of Mechanical Engineering.

7.2 MICROCOMPUTER DESIGN SYSTEM

Plate 7.1 presents an overall view of the microcomputer design system. The microcomputer is a Sperry IT Personal Computer, based on a 80286 microprocessor with 80287 numeric co-processor. The system has been configured in a dual display mode. That is, one monitor is dedicated to text display, and the larger monitor displays all graphics output. This configuration is well suited to the processing and analysis of the experimental flow properties because data points may be edited via the text monitor while viewing the graphical presentation on the adjacent display. Plate 7.2 presents a view of both displays to highlight this feature. In a
Plate 7.1: View of the Microcomputer Design System.
Plate 7.2: View of the Microcomputer Displays, Highlighting the Dual Screen Configuration.
single monitor configuration the operator would need to switch alternatively between text and graphics modes in using this software.

Enhancements to this Sperry computer include 1.2 megabyte and 360 kilobyte floppy disc drives, 40 megabyte hard disc drive, 2 megabyte extended memory (often termed virtual disk), and one parallel and two serial communication ports. Computer peripherals (presented in Plate 7.1) include a NEC P7 Pinwriter printer for producing typed reports and a Mutoh IP-500 multi-pen plotter for the plotting of flow property graphs and hopper design graphs.

Graphical output is achieved by a Vectrix VX/PC Graphics card (developed by Vectrix Corporation, USA) and displayed on the Electrohome DO3 Series 19" RGB colour monitor. Features of the graphics card include a high level graphics command language, a screen resolution of 672 x 480 pixels with 4096 possible colours and nine bitplanes.

The programs developed for the microcomputer operate within the MS-DOS operating environment. They are programmed in FORTRAN and compiled by the F77L FORTRAN compiler (licensed product from Lahey Computer Systems Inc., USA.). This compiler was selected because it was considered to be the closest aligned to the ANSI FORTRAN Standard X3.9-1978, and, compared to other compilers, had superior speed in terms of execution time and features such as an on-line debugging and subroutines for DOS system access. Linking or mapping of the compiled machine code into executable programs was achieved using PLINK 86+, (licensed product from Phoenix Technologies Ltd. USA.). Features of this linker include complex code overlay management for RAM swapping and the ability to form compiled libraries of code.
The data input and output from the microcomputer programs is an important aspect. Data file access within MS-DOS has been incorporated allowing read/write operations to files in branched directories or sub-directories existing on the hard disk or floppy disks. Thus, for subsequent executions of a program, the data does not need to be retyped, but only the data file directory location specified. Output files which store processed report summaries for printing, and graphic data files for plotting are generated automatically by the programs. These features will be highlighted in the respective discussions of each program.

Communication with the Vectrix Card for graphical output was achieved using a University developed FORTRAN PLOT PACKAGE [63] transferred and recompiled on the microcomputer. The graphic command strings are post-processed to convert the code into HP-GL, (Hewlett-Packard Graphics Language), which is required for controlling the Mutoh plotter. Background plotting of graphics is achieved by using the memory resident utility program AutoPLOT II (licensed product from DSL Inc., USA.). This allows the operator to be executing one of the bulk materials programs while the microcomputer is also communicating graphics commands to the plotter.

Incorporation of user-friendly aspects in the development of both programs for the microcomputer system has received a high priority. Features include:

- a full screen editor for interactive data input/adjustment
- a hierarchical menu structure where repeated ESC keystrokes will return the operator from any module branch to the root menu.
- extensive use of the ANSI Escape sequences for formatting of the text monitor with controlled cursor positioning and highlighted text. Advanced keyboard read sequences also allow single
keystroke responses to option selections (rather than requiring an additional RETURN keystroke).

- default responses supplied for many of the option selections.
- An interactively controlled information page facility to aid operator familiarisation of the program structure and execution.

The complete FORTRAN computer code of both programs has not been included in the Appendix because of the large amount of code. However, interested readers are invited to contact the author should they require further detailed information.

Each computer program will now be considered in detail. As the development of the programs for the microcomputer was the most recent, details and features relate particularly to this system.

7.3 COMPUTER PROCESSING AND ANALYSIS OF THE FLOW PROPERTIES OF BULK SOLIDS; PROGRAM FP

The program FP allows the rapid processing and analysis of the considerable amounts of experimental data obtained from the flow property testing of the bulk solid materials. The interactive format of the program has particular advantages in the processing of experimental data, since editing features and the graphical output displays allow the adjustment of doubtful points, and analysis of the data can be repeated until satisfactory, within the same program execution session. The presentation of the flow property results graphically has provided an invaluable aid in highlighting doubtful data points. It also provides a quick and convenient means of obtaining permanent copies of the flow property variations by means of the Mutoh IP-500 plotter.
In addition to providing the graphical output, each of the flow properties are described by an empirical equation that is curve-fitted to the relevant data by various regression techniques.

The FP program consists of 6,868 lines of FORTRAN code arranged in 38 symbolic files (excluding the PLOT PACKAGE and IMSL routines). Appendix I.1 presents a summary of the size (bytes) and number of lines of each file. The size of the executable file FP.EXE is 448 kilobytes. Figure 7.1 presents a flow chart of FP at the root menu level. It can be seen that maximum flexibility has been provided in being able to select the required options, and on completion of the task, return to this root menu. The code listing of FPMAIN.FOR, the main calling program which controls the root menu is provided in Appendix I.2. There are substantial menus of lower hierarchical status from each of the major options. These control such features as data input and editing functions, graphical display options and engineering units.

It is not intended to provide a full discussion of the laboratory procedures involved in the flow property testing. These have been fully documented in References [3,4] and discussed in Chapter 2. Before presenting a detailed description of each major option, the characteristic empirical equations (and the procedures in determining the parameter values) used in describing the respective flow properties will be discussed.

7.3.1 Representation of Flow Properties by Empirical Equations

To allow subsequent computer programs, such as the bin design program, BD, to utilise iterative design procedures based on the bulk solid flow properties, they must be described by empirical equations. These continuous functions allow the bin design program to calculate the critical design values with greater accuracy and speed than by considering discrete point values representing the flow property variations. Table 7.1 presents a
Start

Enter Data Filenames and Bulk Solid Material Details

Select Flow Property Option from the Root Menu:
ESC : Finish Program
F1 : Instantaneous Yield Locus and Flow Function
F2 : Time Yield Locus and Time Flow Function
F3 : Wall Yield Locus
F4 : Kinematic Angle of Wall Friction
F5 : Bulk Density Variation

F1
- Low and High Pressure Instantaneous Yield Loci
- Present Resulting Flow Function and/or Extended Flow Function
- Present Variations of d with Consolidation Stress
- Fit Empirical Equations to Flow Functions and d Variations

F2
- Low and High Pressure Time Yield Loci
- Present Resulting Time Flow Function and/or Extended Time Flow Functions, including Previous Instantaneous Flow Function
- Present Variation of ft with Consolidation Stress
- Fit Empirical Equations to Flow Functions and ft Variation

F3
- Wall Yield Loci for a Limit of 10 Wall Lining Materials
- Fit Empirical Equations to Describe the Wall Yield Loci

F4
- Present the Kinematic Angle of Wall Friction Variation with Consolidation Stress, for a Limit of 10 Wall Lining Materials

F5
- Present the Variation of Bulk Density Variation with Consolidation Stress in Linear and Logarithmic Graphical Formats
- Fit the Empirical Equation to Describe the Bulk Density Variation

Figure 7.1: Flow Chart of Computer Program FP.
Instantaneous Flow Function:
\[ \sigma_c = 0.40 \sigma_1 + 0.63 \]

2 Day Time Flow Function:
\[ \sigma_{ct} = 0.42 \sigma_1 + 0.95 \]

Effective Angle of Internal Friction Variation:
\[ \delta = 16.71 + \frac{1964.28}{33.66 + \sigma_1} \]

Static Angle of Internal Friction Variation:
\[ \phi_t = 0.01 \sigma_1 + 35.10 \]

Bulk Density Variation:
\[ \rho = 787.14 \left( \frac{\sigma_1}{5.925} \right)^{0.0767} \]

Wall Yield Locus Equations

Rusty Mild Steel:
\[ \tau = 51.78 - \frac{4195.07}{81.25 + \sigma} \]

304-2B Stainless Steel:
\[ \tau = 0.25 \sigma + 0.37 \]

Table 7.1:  Typical Empirical Flow Property Equations
The flow properties of the instantaneous and time flow functions, effective angle of internal friction, static angle of internal friction and the wall yield loci can be adequately described by either:

- a straight line (form $Y = mX + b$)
- a three parameter equation originally suggested by Johanson and Carson [65]. This equation has the form $Y = A - \frac{B}{(C+X)}$ where $A$, $B$ and $C$ are constants.

The three parameter equation is advantageous for computer applications in being able to represent flow properties of both concave and convex forms by suitable selection of the signs and relative values of each of the constants. Considering the three parameter equation further, the following aspects are important:

- as $X \to \infty$, $Y \to A$, with an asymptotic variation.
- for $X = 0$, the $Y$ intercept is $Y = A - \frac{B}{C}$
- for a positive $B$, the three parameter variation is convex upward.
  However, for a negative $B$, the equation form becomes $Y = A - \frac{B}{(C+X)}$, and the variation is concave downward. This second form is particularly useful for curve fitting the effective angle of internal friction variation.
- the rate of decay is dependent on the relative absolute values of $B$ and $C$.

The variation of bulk density with major consolidation stress is adequately described by a power equation of the form $\rho = \rho_0 \left(\frac{\sigma}{\sigma_0}\right)^b$. It will be realised that using log format, this relation gives a straight line with a
a gradient of 'b' and passing through the centroid of the experimental data $(\sigma_o, \rho_o)$.

The two equation forms (linear or three parameter) are curve-fitted to the experimental data by implementing one of the following regression techniques:

- least squares regression,
- constrained Rosenbrock Hillclimb [66],
- unconstrained Fletcher-Powell optimisation [66].

Acceptance of a particular equation is based on a visual acceptance of the graphical output. A characteristic of the optimisation techniques, particularly the constrained Rosenbrock method is the dependence of the optimised solution on the initial starting points selected. As a result a starting point algorithm has been developed to allow the user to select suitable starting points or allow these to be selected with regard to certain ratios [61]. The constrained Rosenbrock Hillclimb is required for particular flow properties, to override the experimental data if necessary. Such cases include:

- Constraining the flow functions, wall yield loci and the static angle of internal friction to have a convex upward variation.
- Constraining the flow functions to pass through the origin if a positive abscissa (X-axis) intercept occurs.
- Constraining the effective angle of internal friction to a concave downward variation. Additional constraints force a positive ordinate intercept maximum limit of $80^\circ$. A straight line will be curve fitted if the data actually presents a convex upward variation.
Several shortcomings found with the use of the Rosenbrock method (particularly in terms of computation time) were eliminated by implementing the Fletcher-Powell method, which, while not providing a constrained solution, is more flexible with regard to starting points and speed of convergence.

7.3.2 Execution of Program FP

The operation and features of this program is best highlighted by an example, and a ROM coal at 10% moisture content will be used for this purpose. Printouts of the text monitor screen are presented with this discussion to illustrate the operator/program interaction for the various options.

On starting the program by typing `\FP\FP`, and loading of the code into memory, the text screen displays the titlepage, Figure 7.2. The initial considerations of the program are the data file input and output operations. For efficient system management and recording the results of each execution session, FP can be executed from the operator's personal MS-DOS directory, rather than the root directory. This approach ensures that for several operators the respective data files (which can be custom named) will reside in the directory of the operator and not be liable to corruption or erasure by other users.

On leaving the titlepage, the bulk solid characteristics are entered through the display depicted in Figure 7.3. The details entered will be later appended to each of the graphical presentations, as part of the titleblock. As indicated in Figure 7.3, the uppermost three lines of each text screen contains a status bar to inform the user of the current location in the program or option.
Figure 7.2: Titlepage of Program *FP*. 

Press H for help or any key to continue.
ENTER MATERIAL DATA AS REQUESTED

MATERIAL TESTED: RUN OF MINE COAL

MOISTURE CONTENT: 10% Nom.

DATE TESTED: JANUARY, 1988

TEMPERATURE <AMBIENT>:

Figure 7.3: Entry of Bulk Solid Characteristics.

REPORT FILE ASSIGNMENT

PROCESSED DATA STORAGE FILE <REPORT>: ROM-REP

PLOT STORAGE FILES CODE NAME <FP>: ROM-P

Figure 7.4: Setup of Data Output Files.
Two major output data files are involved in the program operation. As presented in Figure 7.4, the first file contains the processed flow property data and empirical equations arranged in a report format, (Appendix 1.3 presents the report processed from the example). The second data file stores graphical displays selected by the operator for plotting during or after the current execution session. As indicated specific file names may be entered, otherwise the default names are used by responding with a RETURN keystroke.

This completes the initial information required by FP, and the root menu of the program is then displayed (Figure 7.5). Option selection is achieved by using the programmable function keys provided on most IBM-PC compatible computer keyboards. Pressing ESC terminates the program execution.

The operation and features of the various options will now be presented based on a set of experimentally determined flow property data from the coal testing program.

7.3.3 Instantaneous Yield Locus

The basic flow property test is the determination of the family of instantaneous yield loci using the standardised procedure presented in Appendix A. The shear strength is determined under various normal stresses at normally three consolidating pressures to produce the family of yield loci. For each yield locus, two Mohr circles of stress can be drawn tangential to the locus: one passing through the origin defining the unconfined yield stress (\( \sigma_c \)) and the second, passing through the steady state shear co-ordinates, determining the major consolidation stress (\( \sigma_1 \)).
FLOW PROPERTY TESTS AVAILABLE

WHICH FLOW PROPERTY TEST DO YOU REQUIRE TO PROCESS

ESC - FINISH
F1 - INSTANTANEOUS YIELD LOCI AND FLOW FUNCTION
F2 - TIME YIELD LOCI AND FLOW FUNCTIONS
F3 - WALL YIELD LOCI
F4 - KINEMATIC ANGLE OF WALL FRICTION VARIATION
F5 - BULK DENSITY VARIATION

OPTION

Figure 7.5: Root Menu of Program FP.
Several researchers have considered the yield loci to be convex upward and to be adequately described by the so-called Warren-Spring equation [58]:

$$\left(\frac{\tau}{c}\right)^n = \frac{\sigma}{T} + 1$$  \hspace{1cm} (7.1)

where \(c\), \(n\), and \(T\) are constant.

Experience has shown that the yield loci can be conveniently represented by straight line segments. By comparison with the convex yield loci, this approach generally produces larger values for the unconfined stress \(\sigma_c\) and hence more conservative design data. The straight line representation has the advantage of leading to simplified mathematical relations to determine:

- the effective angle of internal friction
- the unconfined yield stress
- the major consolidation stress.

It is essential that this computer program be regarded as an aid to producing graphical representations of the yield loci and not as a replacement for the hand drawn graph which must be obtained during the course of shear testing in the laboratory. To allow the correct interpretation on the experimental data the observations and valid ranges detailed in Appendix A.5 and Figure A.4 must be adhered to.

Figure 7.6 presents the first text screen of option F1, for the data entry of the instantaneous yield loci from either the keyboard or data file. If the keyboard entry approach is selected the program first prompts for a filename to store the experimental values (to allow data file entry for subsequent program runs) and then displays Figure 7.7 for the input of data for each consolidation level. For this text screen, cursor positioning adjacent to each respective text string occurs allowing rapid and convenient data
INSTANTANEOUS YIELD LOCI DETERMINATION

DATA ENTRY METHOD:

F1 - KEYBOARD
F2 - DATA FILE

OPTION

OUTPUT FILE <.DAT> ROM-IYL.DAT

ARE THE UNITS IN 0:POUNDS, 1:NEWTONS OR 2:KILOPASCALS  0

NUMBER OF YIELD LOCI  3

Figure 7.6: Data Input of Experimental Values into the Instantaneous Yield Loci Module.
**INSTANTANEOUS YIELD LOCI DETERMINATION**

**YIELD LOCUS 1:**

**END POINT OF YIELD LOCUS \((V,S)\) \(7.84\ \ 8.05\)**

**NUMBER OF POINTS ON YIELD LOCUS** \(4\)

**ENTER YIELD LOCUS POINTS**

\[(\text{NORMAL FORCE, SHEAR FORCE})\]

\[
\begin{align*}
4.84 & \quad 6.3 \\
3.84 & \quad 5.5 \\
3.34 & \quad 5.1 \\
2.84 & \quad 4.7 \\
\end{align*}
\]

**YIELD LOCUS 2:**

**END POINT OF YIELD LOCUS \((V,S)\) \(5.84\ \ 6.19\)**

**NUMBER OF POINTS ON YIELD LOCUS** \(4\)

**ENTER YIELD LOCUS POINTS**

\[(\text{NORMAL FORCE, SHEAR FORCE})\]

\[
\begin{align*}
3.83 & \quad 5.06 \\
3.33 & \quad 4.71 \\
2.83 & \quad 4.33 \\
2.33 & \quad 3.83 \\
\end{align*}
\]

**YIELD LOCUS 3:**

**END POINT OF YIELD LOCUS \((V,S)\) \(3.82\ \ 4.1\)**

**NUMBER OF POINTS ON YIELD LOCUS** \(3\)

**ENTER YIELD LOCUS POINTS**

\[(\text{NORMAL FORCE, SHEAR FORCE})\]

\[
\begin{align*}
2.32 & \quad 3.4 \\
2.07 & \quad 3.1 \\
1.82 & \quad 2.92 \\
\end{align*}
\]

**Figure 7.7:** Text Screen Arrangement for Data Input into the Instantaneous Yield Loci Module.
entry. The program caters for a maximum of five consolidation levels each consisting of six yield loci coordinates. The program provides checks on the data to ensure the yield locus fitted does not lie below the shear consolidation value (V,S) or have a negative cohesion value (C, Figure A.4).

On completion of the data entry, an intermediate menu is displayed, allowing the user to return to the root menu, edit data for typing errors or display graphs of the instantaneous yield loci. Option F4 allows the instantaneous flow function to be superimposed over the instantaneous yield loci. Figure 7.8 presents a typical display for this option, which has proved useful in checking of experimental yield loci data.

At the completion of the plot (displayed on the graphics monitor) the text screen displays the main menu for the instantaneous yield loci options, presented in Figure 7.9. As indicated the important parameters of \( \sigma_i \), \( \sigma_c \) and \( \delta \) are tabulated for each consolidation level.

No facility has been provided in the program for automatically weighting individual data points. However, in determining the family of instantaneous yield loci, it is often necessary to shift slightly the shear values associated with individual data points as the computer program treats each yield locus individually. An editing option, F1, allows this manual adjustment of the data points. Figure 7.10 presents the text screen format of this option. The editor has a full screen format, meaning that the complete yield data for each consolidation level is displayed and individual normal or shear data values can be edited separately, rather than retyping the complete coordinate. The YIELD LOCUS and UNITS status lines allow the different data formats to be selected by positioning the cursor on the relevant option. For instance, the yield loci data can easily be edited in either pounds of kilopascals by selecting the required term in the UNITS status line.
Figure 7.8: Instantaneous Flow Function Superimposed over the Instantaneous Yield Loci.

INSTANTANEOUS YIELD LOCI DETERMINATION

<table>
<thead>
<tr>
<th>SIGMA1(kPa)</th>
<th>SIGMAC(kPa)</th>
<th>DELTA(Degree)</th>
<th>PHI(Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.88</td>
<td>6.29</td>
<td>53.51</td>
<td>38.66</td>
</tr>
<tr>
<td>8.99</td>
<td>5.18</td>
<td>55.57</td>
<td>39.15</td>
</tr>
<tr>
<td>5.71</td>
<td>3.77</td>
<td>59.64</td>
<td>40.03</td>
</tr>
</tbody>
</table>

SELECT REQUIRED OPTION

ESC - RETURN TO MAIN MENU
F1 - EDIT YIELD LOCI DATA
F2 - CALCULATE PARAMETER TABLE, WITHOUT PLOT
F3 - DISPLAY PLOT
F4 - PLOT WITH FLOW FUNCTION
F5 - DISPLAY V1 AND F IN POUNDS
F6 - CURVE FIT AND PLOT FLOW FUNCTION
F7 - PROCESS HIGH PRESSURE YIELD LOCI DATA

OPTION

Figure 7.9: Main Menu of the Instantaneous Yield Loci Module.
### Instantaneous Yield Loci Determination

<table>
<thead>
<tr>
<th>Units</th>
<th>Pounds</th>
<th>Newtons</th>
<th>Kilonewtons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End Point (V,S)</strong></td>
<td>4.882</td>
<td>5.013</td>
<td></td>
</tr>
<tr>
<td><strong>Locus Points (V,S)</strong></td>
<td>3.014</td>
<td>3.923</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.391</td>
<td>3.425</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.080</td>
<td>3.176</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.769</td>
<td>2.927</td>
<td></td>
</tr>
</tbody>
</table>

### Instantaneous Yield Loci Determination

<table>
<thead>
<tr>
<th>Units</th>
<th>Pounds</th>
<th>Newtons</th>
<th>Kilonewtons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End Point (V,S)</strong></td>
<td>3.637</td>
<td>3.855</td>
<td></td>
</tr>
<tr>
<td><strong>Locus Points (V,S)</strong></td>
<td>2.385</td>
<td>3.151</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.074</td>
<td>2.933</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.762</td>
<td>2.696</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.451</td>
<td>2.385</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.10: Typical Display for the Editing of Experimental Data Values.
Figure 7.11 presents the final instantaneous yield loci graph processed for the example. Note that the graphical axes are automatically scaled to produce the clearest and most convenient presentation of the data.

On pressing ESC the user is returned to the root menu and the respective values of $\sigma_t$, $\sigma_c$ and $\delta$ for each consolidation level are stored for later presentations.

7.3.4 Time Yield Loci

The gain in strength of the bulk solid due to time storage at rest may be assessed by considering the family of time yield loci. These loci also conform to the observations listed in Appendix A.5, with the additional observation that is unusual for the values of $\sigma_{ct}$ to be less than $\sigma_c$. If this occurs it usually indicates erroneous experimental data.

The data entry section of the time yield loci module is similar to that of the previous instantaneous yield loci option except that the period of time consolidation is also entered, and the data for each consolidation level is linked to the previously entered instantaneous data.

On completion of the data input, the values of $\sigma_t$, $\sigma_{ct}$ and $\phi_t$ are tabulated for each consolidation level (Figure 7.12). To aid the adjustment of the time yield loci, option F4 allows the instantaneous flow function and the time flow function to be superimposed over the time yield loci currently being processed. This allows the time yield loci to be checked indirectly by comparison of the data points $(\sigma_t, \sigma_{ct})$ against the instantaneous flow function as indicated in Figure 7.13. Data can be adjusted if required using the same editing facilities as the instantaneous yield loci module. Figure 7.14 presents the final time yield loci graph.

On exit from this module the values of $\sigma_{ct}$ and $\phi_t$ for respective values of $\sigma_t$ are stored for later presentations.
Figure 7.11: Typical Instantaneous Yield Loci Plot.
TIME YIELD LOCI DETERMINATION

<table>
<thead>
<tr>
<th>SIGMA1 (kPa)</th>
<th>SIGMACT (kPa)</th>
<th>PHI (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.88</td>
<td>7.06</td>
<td>43.5</td>
</tr>
<tr>
<td>8.99</td>
<td>5.91</td>
<td>40.5</td>
</tr>
<tr>
<td>5.71</td>
<td>4.40</td>
<td>40.6</td>
</tr>
</tbody>
</table>

PLOT OPTION

ESC - RETURN TO MAIN MENU
F1 - EDIT YIELD LOCI DATA
F2 - CALCULATE PARAMETERS, WITHOUT PLOT
F3 - PLOT TIME YIELD LOCI DATA
F4 - PLOT TIME YIELD LOCI DATA WITH FLOW FUNCTIONS
F5 - DISPLAY V1 AND FT IN POUNDS
F6 - PLOT INSTANTANEOUS AND TIME FLOW FUNCTION
F7 - PROCESS HIGH PRESSURE YIELD LOCI DATA

Figure 7.12: Main Menu of the Time Yield Loci Module.

Figure 7.13: The Instantaneous and Time Flow Functions Superimposed over the Time Yield Loci.
Figure 7.14: Typical Time Yield Loci Plot.
7.3.5 Instantaneous and Time Flow Function, and the Variation of Effective Angle of Friction and Static Angle of Internal Friction

Considering the instantaneous and time yield loci (Figures 7.11 and 7.14 respectively), the variation of $\sigma_e$ and $\sigma_{et}$ can be presented as a function of $\sigma_i$ to form the instantaneous and time flow functions essential to the hopper design procedure. For convenience this presentation has been extended to include the variations of $\delta$ and $\phi_t$.

This graph is constructed by selecting option F6 from either the instantaneous or time yield loci modules. Figure 7.15 presents the first text screen displayed, where for each flow function and the variations of $\delta$ and $\phi_t$ the various plotting options are applied. Figure 7.16 presents a typical plot of this presentation. In addition to the graphical presentation, empirical equations are curve-fitted to the data. The equation values for each flow property are displayed on the text monitor (Figure 7.17), with final acceptance of the curve fit based on visual acceptance of the graphical presentation.

The facility is provided for the user to return directly to the root menu, select new curve-fitting options or return to the respective yield loci module for data editing.

7.3.6 Wall Yield Loci and the Kinematic Angle of Wall Friction

To achieve reliable mass flow design it is important that the frictional characteristics of proposed bin and hopper wall materials with the bulk solid are assessed. This information is obtained from a Coulomb friction test detailed in References [3, 4]. Options F3 and F4 of the root menu of FP allow the wall friction characteristics to be investigated.
FLOW FUNCTION & FRICTION ANGLE VARIATIONS

INSTANTANEOUS FLOW FUNCTION PLOT OPTION
ENTER YOUR CHOICE FOR EACH SET OF DATA
ESC - OMIT FLOW PROPERTY FROM PLOT
F1 - PLOT DATA POINTS ONLY
F2 - PLOT STRAIGHT LINE EQUATION
F3 - PLOT THREE PARAMETER EQUATION

OPTION

EFFECTIVE ANGLE OF FRICTION PLOT OPTION
ENTER YOUR CHOICE FOR EACH SET OF DATA
ESC - OMIT FLOW PROPERTY FROM PLOT
F1 - PLOT DATA POINTS ONLY
F2 - PLOT STRAIGHT LINE EQUATION
F3 - PLOT THREE PARAMETER EQUATION

OPTION

STATIC ANGLE OF INTERNAL FRICTION PLOT OPTION
ENTER YOUR CHOICE FOR EACH SET OF DATA
ESC - OMIT FLOW PROPERTY FROM PLOT
F1 - PLOT DATA POINTS ONLY
F2 - PLOT STRAIGHT LINE EQUATION
F3 - PLOT THREE PARAMETER EQUATION

OPTION

PLOTTING OPTION
ESC - BY-PASS PLOT
F1 - DISPLAY PLOT

OPTION

Figure 7.15: Selection of Curve-Fitting and Plotting Options within the Flow Function Module.
Figure 7.16: Typical Display of Flow Functions, δ and \( \phi_t \) Variations.

FLOW FUNCTION & FRICTION ANGLE VARIATIONS

LOW PRESSURE FLOW PROPERTY EQUATIONS

INSTANTANEOUS FLOW FUNCTION

\[
F = 0.41\sigma_1 + 1.46
\]

EFFECTIVE ANGLE OF INTERNAL FRICTION

\[
\text{DELTA} = 1.52 - \frac{3358.91}{52.71 + \sigma_1}
\]

TIME FLOW FUNCTION

\[
\text{FT} = 0.43\sigma_1 + 1.96
\]

STATIC ANGLE OF INTERNAL FRICTION

\[
\text{PHIT} = 0.46\sigma_1 + 37.44
\]

ESC - RETURN TO MAIN MENU
F1 - SELECT ALTERNATIVE PLOT COMPOSITION
F2 - RETURN TO EDIT YIELD LOCI DATA

Figure 7.17: Text Monitor Display of Empirical Equations within the Flow Function Module.
Considering the first option, this approach presents the wall yield loci data as the variation of shear stress with normal stress. After entry of the experimental data for each wall material (Figure 7.18) the program displays a set of plotting and curve-fitting options applicable to each wall material. Alternatively data can be edited for typing errors or adjustment of dubious experimental values. These plotting options are presented in Figure 7.19. After responding to each wall material the consequent plot is displayed, Figure 7.20, and the wall yield loci equations presented on the text monitor, (Figure 7.21).

Comparison between different wall yield loci, regarding actual values of $\phi$, can be difficult because:

- Wall yield loci often have a convex upward curved variation.
- For moist bulk solids, wall yield loci often have an adhesion component at zero normal stress.
- The variation of effective angle of internal friction and its effects on $\phi$ is difficult to assess.

For the above reasons a direct comparison of the variation of $\phi$ with $\sigma_1$ is far more informative than dealing solely with wall yield loci. As depicted in Figure 7.21, the user has the option to transfer to the kinematic angle of wall friction module, and process the wall yield loci equations just determined. This module can also be accessed directly from the root menu by selecting option $F4$, to calculate and display the $\phi$ variations for previously determined wall yield loci equations.
WALL YIELD LOCI

WALL MATERIAL TESTED: RUSTY MILD STEEL

IS THE DATA IN 0:POUNDS, 1:NEWTONS OR 2:KILOPASCALS: 0

NUMBER OF POINTS ON WALL YIELD LOCUS: 10

ENTER WALL YIELD LOCUS POINTS
(NORMAL FORCE, SHEAR FORCE)

0.81 0.6
2.81 2.1
4.81 3.4
6.81 4.6
8.81 5.5
10.81 6.98
12.81 7.96
14.81 8.73
16.81 10.08
18.81 11.0

WALL MATERIAL TESTED: PACTENE

IS THE DATA IN 0:POUNDS, 1:NEWTONS OR 2:KILOPASCALS: 0

NUMBER OF POINTS ON WALL YIELD LOCUS: 10

ENTER WALL YIELD LOCUS POINTS
(NORMAL FORCE, SHEAR FORCE)

0.81 0.54
2.81 1.29
4.81 2.0
6.81 2.64
8.81 3.38
10.81 4.03
12.81 4.65
14.81 5.48
16.81 6.23
18.81 6.99

WALL MATERIAL TESTED: 304-2B STAINLESS STEEL

IS THE DATA IN 0:POUNDS, 1:NEWTONS OR 2:KILOPASCALS: 0

NUMBER OF POINTS ON WALL YIELD LOCUS: 10

ENTER WALL YIELD LOCUS POINTS
(NORMAL FORCE, SHEAR FORCE)

0.81 0.72
2.81 1.35
4.81 1.94
6.81 2.55
8.81 3.12
10.81 3.68
12.81 4.2
14.81 4.8
16.81 5.36
18.81 5.82

Figure 7.18: Entry of Experimental Wall Yield Loci Data.
WALL YIELD LOCII

PLOT OPTION FOR EACH WALL MATERIAL

ESC - OMIT FROM PLOT
F1 - PLOT DATA POINTS ONLY
F2 - PLOT STRAIGHT LINE EQUATION
F3 - PLOT THREE PARAMETER EQUATION (CONSTRAINED)
F4 - PLOT THREE PARAMETER EQUATION (UNCONSTRAINED)
F5 - TO MODIFY DATA

RUSTY MILD STEEL

304-2B STAINLESS STEEL

Figure 7.19: Selection of Curve-Fitting and Plotting Options within the Wall Yield Option.
Figure 7.20: Typical Display of the Wall Yield Loci.

WALL YIELD LOCI

WALL YIELD LOCI EQUATIONS

RUSTY MILD STEEL \[ S = 0.57*\sigma + 0.30 \]
PACTENE \[ S = 0.35*\sigma + 0.16 \]
304-2B STAINLESS STEEL \[ S = 0.28*\sigma + 0.35 \]

SELECT THE OPTION REQUIRED

ESC - RETURN TO MAIN MENU.
F1 - REPROCESS WALL YIELD LOCI DATA
F2 - PLOT VARIATION OF KINEMATIC ANGLE OF WALL FRICTION

Figure 7.21: Text Monitor Display of Empirical Equations within the Wall Yield Loci Module.
The kinematic angle of wall friction module allows the variation of $\phi$ to be presented in several graphical formats. The axis scales may be manually specified for the full screen display option, to achieve the optimum presentation of the values for the particular region of interest. For example, the region of interest for mass flow hopper geometries is generally bounded by $\sigma_i$; $1.0 < \sigma_i < 10.0$ kPa and $15^\circ < \phi < 30^\circ$. The menu structure also allow the graph to be composed of different wall materials, omitting or including the respective $\phi$ variations according to the users' requirements. Figure 7.22 presents a graph comparing the $\phi$ variation for the three wall materials whose yield loci were depicted in Figure 7.20.

Note that the kinematic angle of wall friction is not curve-fitted by an empirical equation, but presented only in graphical format. The program is also has the option to neglect the effect of $\delta$ in the calculation of the $\phi$ variation. Thus a graph of angle of wall friction variation with normal stress, $\sigma$, is prepared, which is useful for the design of transfer chutes.

7.3.7 Bulk Density

Bin design requires the variation of bulk density with consolidation stress be known. Selection of option F5 of the root menu displays the data input screen of the bulk density module, Figure 7.23. The data can be entered as either raw experimental readings (ie. consolidation load and indicator height readings), or in terms of consolidation stress and bulk density. As indicated in Figure 7.23, data entry is straightforward by responding to the computer prompts. This module curve-fits the power equation form to the data and allows the graphical presentation to be either linear or logarithmic format, as presented in Figure 7.24 and 7.25 respectively.
Figure 7.22: Typical Variation of $\phi$ for Several Wall Materials.
BULK DENSITY VARIATION

ENTER GROSS = TARE IF DATA IS PROCESSED & IN KPA, KG/M**3
GROSS MASS AND TARE MASS (GRAMS) 355.13 322.8

NUMBER OF COMPRESSIBILITY OBSERVATIONS 7

LOAD ON CELL (KG), INDICATOR READING (INS)
OBSERVATION 1: 0.12 0.623
OBSERVATION 2: 0.62 0.567
OBSERVATION 3: 1.12 0.539
OBSERVATION 4: 2.12 0.517
OBSERVATION 5: 4.12 0.491
OBSERVATION 6: 8.12 0.468
OBSERVATION 7: 16.12 0.446

Figure 7.23: Data Entry of Experimental Values into Bulk Density Module.
Figure 7.24: Typical Bulk Density Variation

Figure 7.25: Typical Bulk Density Variation, Logarithmic Format.
7.3.8 Termination of a FP Computing Session

Selection of ESC from the root menu terminates the program operation and a summary of the computing session is displayed on the text monitor. This page provides information regarding the names and sizes of the graphical and text data files. The report summary compiled from processing the ROM coal example is presented in Appendix I.3

7.4 DETERMINATION OF MASS FLOW HOPPER GEOMETRY PARAMETERS; PROGRAM BD

The second computer program, BD, determines the hopper geometry design parameters for mass flow hoppers based on the empirical equations representing the flow properties of the particular bulk solid (refer to Table 7.1). The interactive operation of this program allows the user complete flexibility in deciding the tasks of a computing session. For example, entering (or editing) the relevant flow property equations and then determining the geometry parameters for instantaneous or time storage conditions with the proposed wall lining materials. Figure 7.26 presents the overall flow chart of BD and highlights this feature.

The BD consists of 2,218 lines of FORTRAN code arranged in 24 symbolic files (excluding the PLOT PACKAGE and IMSL routines). Appendix J.1 presents a summary of the size (bytes) and number of lines of code for each file. The size of the executable file BD.EXE is 240 kilobytes. The code listing of BDMAIN.FOR, the main calling program controlling the root menu of the program is provided in Appendix J.2.

A major consideration of the program development is the calculation of the flow factor, which is required to utilise the flow-no flow concept depicted in Figure 1.2. The computer procedures must be mathematically robust to successfully operate with the various
Figure 7.26: Flowchart of the Program BD.
combinations of flow function, wall yield loci and effective angle of internal friction possible.

Figure 7.27 presents the general classifications of bulk solids, namely, free flowing, simple and cohesive according to the respective flow functions. Referring to Figure 7.27, critical arching dimensions and hopper wall slopes can only be determined on the basis of cohesive arching for those flow functions (FF-C) that intersect with relevant flow factor, while the geometry parameters for a simple bulk solid (FF-B) are determined on the basis of wall friction. No mass flow hopper geometry can be determined for the bulk solid indicated by the flow function FF-D as it lies above the flow factor and no intersection can occur. For this situation other forms of storage using non-gravity reclaim methods must be employed.

For the program as first developed, Dwight [62] developed an iterative procedure which converges to the critical value of $\sigma_1$ and $\eta$. This approach is necessary because the flow properties are expressed as a function of $\sigma_1$, and changes in $\eta$ lead to new values of $\sigma_1$ (on intersection with the flow function) and thus new values of $\phi$ and $\delta$. The empirical equations developed by Arnold et al. [4] (Equations 4.2 and 4.3), which express hopper wall slope as a function of $\delta$ and $\phi$, are referenced to provide an $\alpha$ value (on the mass flow boundary, Figure 1.3). Then, knowing the values of $\alpha$, $\phi$ and $\delta$, the flow factor can then be calculated by solving the total differential equations representing the Jenike radial stress field [1] simultaneously under certain boundary conditions. A differential equation solver [64] using a fifth order Runge-Kutta approximation is employed in the solution of these equations.

The updated values of $\phi$ and $\delta$ then allow a new estimate of the flow factor to be found, and the procedure is repeated until the difference between successive flow factor values are within an acceptable tolerance.
Figure 7.27: Bulk Solid Classifications.
(nominally 0.001). A problem with this approach is the excessive computation time involved when either of the following cases occur.

- a mass flow hopper design is not possible for the set of relevant flow properties, eg. the flow function FF-D, Figure 7.27, positioned above the possible range of flow factors.
- a critical mass flow geometry cannot be determined because of high values of wall friction. This typically occurs for bulk solids that have only low to moderately strong flow functions, and a wall yield locus displaying a strong adhesion. As a result, intersections between initial flow factor values and flow function yield values of \( \sigma_1 \) for which \( \phi \) cannot be calculated. This calculation is indeterminate because \( \sigma_1 \) is below the limiting value of \( \sigma_1 \) which defines a Mohr circle of stress that is tangent to the wall yield locus. Thus the Mohr circles generated for smaller \( \sigma_1 \) values do not contact the wall yield locus. Figure F.18 for -0.5mm Westcliff Product coal at 15% moisture illustrates this concept. Here, a value of \( \phi \) cannot be calculated for \( \sigma_1 < 3.0 \) kPa. In this situation, the geometry for mass flow is based on wall friction considerations, (the same as for a simple bulk solid), rather than cohesive arching.

The two aspects discussed above have been eliminated, and the complete critical geometry determination substantially simplified by incorporating the graphical design nomogram procedures developed by Moore and Arnold [48, 67] and discussed in Chapter 5. This is achieved since the complete state of the flow factor variation (unique to the particular set of \( \phi, \delta \) and \( m \)), is represented by the flow factor locus, (refer to Figure 7.28).
Figure 7.28: Computer Application of the Flow Factor Locus Concept for the Determination of the Critical Hopper Geometry.
The computer program follows the operation of the graphical nomogram method, where the intersection between the flow function and the flow factor locus defines the critical design point and the value of $\sigma_1$. This procedure is detailed in Figure 7.28, where for flow function FF-C, point B represents the critical design point.

Representing the flow factor locus by a three parameter equation (with a defined lower endpoint, A), it is computationally straightforward to determine the critical design point by the intersection with the relevant flow function. The endpoint A, represents the lower limit of $\sigma_1$ for which a flow factor can be determined. Further substantial benefits of this approach are realised, when considering the two aspects previously discussed. Referring to Figure 7.28, the flow function positions, such as FF-D, which cannot yield a mass flow hopper geometry can be now easily recognised mathematically (rather than using an iterative procedure).

In relation to the second aspect, Figure 7.28 displays the flow function, FF-B, positioned below the flow factor locus endpoint A, indicating that a critical geometry cannot be determined based on cohesive arching. This flow function is then similar in nature to the simple bulk solid represented by FF-A, with no critical geometry applicable and the variation of $\alpha$ and B is determined by incrementing $\sigma_1$ for values greater than endpoint A.

The other design data presentation determined is the variation of $\alpha$ with span B. As introduced in previous sections, $\phi$ may not be constant but vary with $\sigma_1$, with $\phi$ having high values at low $\sigma_1$ values. This trend is then utilised by allowing larger hopper wall slopes for hopper outlet dimensions above the critical. The increase of consolidation stress with the increased span in turn leads to a reduced $\phi$ value and hence an increased hopper wall slope angle. A typical $\alpha$ versus B graph is depicted in Figure 1.8.
This graph indicates how $\alpha$ tends to a limiting value of $\alpha$ as the rate of change of $\phi$ decreases in the higher stress range of $\sigma_1$. The program $BD$ calculates this variation by incrementing $\sigma_1$ from the critical value to an upper limit of $\sigma_1 = 20$ kPa) and determining the respective values of $\alpha$ and $B$.

The operation of $BD$ will now be described by referring to figures presenting the various text screen and graphics displays. The empirical equations representing the flow properties determined by $FP$ for the ROM coal example will used to determine the hopper geometry parameters.

7.4.1 Execution of Program $BD$

The program execution is started by entering \texttt{BD}\texttt{BD} and the titlepage, Figure 7.29, is displayed after the program has been loaded into memory. After the titlepage, the data output filenames are entered, in a similar fashion to the initial stages of $FP$. The two data output files for $BD$ store a summary of all flow property equations used in the analysis, and the second file stores the graphical displays selected by the operator as plot files.

The next stage involves the input of the bulk solid name and the relevant flow property empirical equations. This information can be entered from the keyboard, or by data file. If the keyboard approach is selected, the operator is requested for a data file name, to store the entered equations for subsequent computing sessions.

Figures 7.30 to 7.36 present the displays of the text monitor for the input of the bulk material name and flow properties. As indicated in these figures, utilising formatted text screens allows the characteristic equation to be displayed and the cursor positioned within each cell for the entry of the coefficients. This technique is a convenient and rapid means of data entry
MASS FLOW HOPPER
GEOMETRY DETERMIATION

DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF WOLLONGONG

Developed by: B.A.MOORE
N.B.MASON

VERSION 2.0
January, 1988

Press H for help or any key to continue

Figure 7.29: Titlepage of Program BD.

BULK SOLID FLOW CHARACTERISTICS

DATA ENTRY METHOD
F1 - KEYBOARD
F2 - DATA FILE

OPTION -

DATA INPUT FILE <BD-INPUT.DAT>: ROM-INPUT.DAT
(FOR SUBSEQUENT RERUNS)

ENTER THE MATERIAL NAME:
RUN OF MINE COAL, 10% Nom.

Figure 7.30: Flow Property Data Input for BD: Bulk Solid Name.
FLOW FUNCTION DATA ENTRY

ESC - NOT AVAILABLE
F1 - INSTANTANEOUS FLOW FUNCTION

OPTION -

SIGMAC = (0.41 ) *SIGMA1+(1.46 ) KPa

Figure 7.31: Flow Property Data Input for BD: Instantaneous Flow Function.

FLOW FUNCTION DATA ENTRY

ESC - NOT AVAILABLE
F1 - TIME FLOW FUNCTION

OPTION -

SIGMAC = (0.43 ) *SIGMA1+(1.96 ) KPa

Figure 7.32: Flow Property Data Input for BD: Time Flow Function.
BULK SOLID FLOW CHARACTERISTICS

EFFECTIVE ANGLE OF INTERNAL FRICTION:

F1 - CONSTANT VALUE
F2 - TWO PARAMETER EQUATION
F3 - THREE PARAMETER EQUATION

OPTION -

\[ \text{DELTA} = (1.52) - \frac{(-3358.91)}{(\sigma_1 + (52.71))} \text{ DEGREES} \]

Figure 7.33: Flow Property Data Input for BD: Effective Angle of Internal Friction.

BULK SOLID FLOW CHARACTERISTICS

EQUATION FOR BULK DENSITY VARIATION

\[ \text{BULK DENSITY} = (775.01) \times \left[ \frac{\sigma_1}{(5.925)} \right]^{**0.0694} \text{ Kg/M}^*3 \]

Figure 7.34: Flow Property Data Input for BD: Bulk Density Variation.
HOPPER GEOMETRY DESIGN

WALL YIELD LOCI DATA ENTRY  ESC - RETURN TO MAIN MENU
F1 - ENTER WALL MATERIAL NAME

OPTION -

WALL MATERIAL NAME FOR W.Y.L. No. 1: RUSTY MS

WALL YIELD LOCI EQUATION: F1 - CONSTANT PHI
F2 - TWO PARAMETER EQUATION
F3 - THREE PARAMETER EQUATION

OPTION -

\[ \tau = (41.00) - \frac{(2344.19)}{(\sigma_1 + (57.21))} \text{ KPa.} \]

Figure 7.35: Flow Property Data Input for BD: Wall Yield Locus, Three Parameter Equation.

BULK SOLID FLOW CHARACTERISTICS

WALL YIELD LOCI DATA ENTRY  ESC - RETURN TO MAIN MENU
F1 - ENTER WALL MATERIAL NAME

OPTION -

WALL MATERIAL NAME FOR W.Y.L. No. 3: 3G4-2B STAINLESS STEEL

WALL YIELD LOCI EQUATION: F1 - CONSTANT PHI
F2 - TWO PARAMETER EQUATION
F3 - THREE PARAMETER EQUATION

OPTION -

\[ \tau = (0.28) \times \sigma_1 + (0.35) \text{ KPa} \]

Figure 7.36: Flow Property Data Input for BD: Wall Yield Locus, Linear Equation.
HOPPER GEOMETRY DESIGN

SELECT FROM THE FOLLOWING

ESC - FINISH
F1 - CALCULATE MASS FLOW HOPPER GEOMETRY
F2 - ALTER BULK SOLID FLOW PROPERTIES

OPTION -

Figure 7.37: Root Menu of Program BD.
and minimises typing mistakes. The program can process up to ten wall materials.

On completion of the data entry of the flow properties, the root menu of BD, Figure 7.37 is displayed. The structure of BD has been arranged to allow additional aspects of bin design to be incorporated as modules in the root menu in the future. Such aspects include funnel flow geometry design, feeder load calculations, bin wall loadings and bin volume/dimension design graphs.

7.4.2 Determination of Mass Flow Hopper Geometry Parameters

On selection of option F1, from the root menu, the text monitor displays Figure 7.38. This is the main menu page for the mass flow geometry determination module and allows the hopper shape and relevant flow properties to be nominated. As indicated, this screen arrangement provides a complete and clearly formatted schedule for each calculation.

After selection of the wall lining material, the program calculates the critical mass flow parameters and displays the results on the text monitor as presented in Figure 7.39. Note the values of $a$ and $B$ have been rounded off in the display, with $a$ to the nearest 0.5° above and $B$ to the nearest multiple of 5mm. Selection of option F3 if more detailed information is required, displays the parameter values at the critical design point involved in the geometry calculation, Figure 7.40.

To generate the $a$ versus $B$ graph, options F1 or F2 are selected from the screen format displayed in Figure 7.39. The first option calculates the relevant values and stores them for subsequent plotting with other graphs for different wall materials or hopper shapes. The second option calculates the variation and displays the plot on the graphics monitor.
## MASS FLOW HOPPER - CRITICAL GEOMETRY PARAMETERS

**BIN GEOMETRY**
- F1 - AXISYMMETRIC
- F2 - PLANE FLOW

**FLOW FUNCTION**
- F1 - INSTANTANEOUS
- F2 - TIME

**WALL MATERIALS**

<table>
<thead>
<tr>
<th>WALL MATERIAL</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUSTY MS</td>
<td>1</td>
</tr>
<tr>
<td>PACTENE</td>
<td>2</td>
</tr>
<tr>
<td>304-2B SS</td>
<td>3</td>
</tr>
</tbody>
</table>

ENTER WALL MATERIAL No. (< 1 >)

Figure 7.38: Main Menu of the Mass Flow Hopper Geometry Module.
**MASS FLOW HOPPER - CRITICAL GEOMETRY PARAMETERS**

**CRITICAL DIMENSION FOR BIN HOPPER GEOMETRY**

<table>
<thead>
<tr>
<th>HOPPER HALF ANGLE</th>
<th>OUTLET WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.5 Degrees</td>
<td>425. mm</td>
</tr>
</tbody>
</table>

**INSTANTANEOUS FLOW FUNCTION**

PLANE FLOW HOPPER GEOMETRY

WALL MATERIAL: 304-2B SS

ESC - RETURN TO MAIN MENU
F1 - DETERMINE ALPHA VS B VARIATION
F2 - DETERMINE AND PLOT ALPHA VS B VARIATION
F3 - DISPLAY PARAMETERS AT CRITICAL DESIGN POINT

**OPTION -**

Figure 7.39: Text Screen Displaying the Critical Mass Flow Hopper Geometry Parameters.

**MASS FLOW HOPPER - CRITICAL GEOMETRY PARAMETERS**

**CRITICAL DIMENSION FOR BIN HOPPER GEOMETRY**

<table>
<thead>
<tr>
<th>HOPPER HALF ANGLE</th>
<th>OUTLET WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.5 Degrees</td>
<td>425. mm</td>
</tr>
</tbody>
</table>

**PARAMETERS AT THE CRITICAL DESIGN POINT**

MAJOR CONSOLIDATION STRESS: 2.911 kPa
CRITICAL FLOW FACTOR: 1.097
KINEMATIC ANGLE OF WALL FRICTION: 22.95 Deg.
EFFECTIVE ANGLE OF INT. FRICTION: 61.91 Deg.

ESC - RETURN TO PREVIOUS MENU

Figure 7.40: Text Screen Displaying the Critical Mass Flow Hopper Geometry Parameters and Flow Property Values at the Critical Design Point.
On returning from the main menu, Figure 7.41, the parameters selected for the previous calculation are displayed as default responses. This provides the operator with a summary of the previous calculation and also allows the rapid selection of parameters for the next calculation. For previously calculated $\alpha$ versus $B$ graphs a facility has been incorporated for merging of different curves. As indicated in Figure 7.42, this provides a clear method of comparing the geometry characteristics of different wall materials in determining the optimum hopper design.

7.4.3 Termination of a BD Computing Session

From the root menu of BD, an ESC keystroke terminates the program operation, and a status summary of the current computing session is displayed on the text monitor. This summary provides information regarding the graphical and text data output files generated during the computing session. The flow property equation summary file generated for the ROM coal example is presented in Appendix J.3.

7.5 CONCLUDING REMARKS

The utilisation of computer software detailed in this chapter, to aid in the processing of experimental flow property data and the determination of suitable hopper design parameters has provided substantial benefits in time savings and increased the consistency and sophistication of the procedures over manual methods. The operation of computer programs FP and BD on a two monitor microcomputer system, utilising a interactive graphic format has demonstrated the advantages for tasks such as the processing and editing of experimental flow property data, the plotting of hopper geometry design graphs and compilation of results. Only with the existence of such software, could the large amounts of flow
### Mass Flow Hopper - Critical Geometry Parameters

<table>
<thead>
<tr>
<th>Bin Geometry</th>
<th>F1 - Axisymmetric</th>
<th>F2 - Plane Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option</td>
<td>(F2)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow Function</th>
<th>F1 - Instantaneous</th>
<th>F2 - Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option</td>
<td>(F1)</td>
<td></td>
</tr>
</tbody>
</table>

### Wall Materials

<table>
<thead>
<tr>
<th>Wall Material</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rusty MS</td>
<td>1</td>
</tr>
<tr>
<td>Factene</td>
<td>2</td>
</tr>
<tr>
<td>304-2B SS</td>
<td>3</td>
</tr>
</tbody>
</table>

Enter Wall Material No. < 3>

---

Figure 7.41: Main Menu of the Mass Flow Hopper Geometry Module Highlighting the Default Responses from the Previous Geometry Calculation.
Figure 7.42: Graphical Presentation of the Variation of $\alpha$ versus $B$ for Several Wall Materials from the Design Example.
property data and hopper geometry parameters presented in Appendices B through G be processed and analysed.

Representing the flow properties by characteristic empirical equations, namely, linear, three parameter and power equations, has proved a convenient and accurate method of specifying the flow properties for input into materials handling design programs. The three parameter equation used to describe some of the flow properties has proved to be most versatile.

The determination of the mass flow hopper geometry parameters by a computer program incorporating the flow factor locus approach [48] (utilised in the graphical nomograms detailed in Chapter 5) has provided a computer algorithm which is more direct and simpler than the previous algorithm which used iterative procedures. Since the flow factor locus describes the complete variation of the flow factor with $\sigma_1$ (unique to the the particular set of $\delta$, $\phi$ and $m$ values), the calculation of hopper geometry parameters can be determined directly by comparing the flow factor locus with flow functions of the bulk solid.
CHAPTER 8
CONCLUSIONS

The design of storage facilities to ensure reliable and predictable performance should be approached as a four step procedure:

- Determination of the strength and other flow properties of the bulk solid for the worst representative conditions likely to occur in practice.
- Determination of the bin geometry to give the desired capacity and to achieve the required flow pattern with acceptable flow characteristics and to ensure that discharge is reliable and predictable.
- Estimation of the loads exerted on the bin walls and feeder under operating conditions.
- Design and detailing of the bin structure and hopper feeder interface.

This work has studied the two initial phases of the above procedure, specifically related to the design of mass flow bins for the storage of black coal. This has involved an investigation of the influence of physical variables of coal samples on the respective flow properties and the design procedures for determination of the mass flow hopper geometry parameters.

8.1 FLOW PROPERTIES OF BLACK COAL

A rigorous flow property testing program was conducted on coal samples from the Southern Coalfields (Illawarra Measures) of the Sydney Basin. This coal is a hard black coal type varying in rank from sub-bituminous to semi-anthracite.
A standardised testing procedure was developed for the Jenike-type Direct Shear Tester. This procedure minimised operator and data interpretation related errors in the shear testing of the coal samples for the flow property testing program. Important aspects of this procedure include the need to consider the yield loci of different consolidation levels as a family of related curves, the yield loci should be parallel or fan out slightly, and that the end points of the yield loci lie on a line passing through or just above the origin. The prorating procedure of Jenike [68] for reducing the scatter of yield loci data coordinates was found to work well.

The testing program identified the physical variables of free moisture content, particle top size and distribution, and time of storage at rest to be the most significant influence on the flow properties. Other factors such as particle shape, coal rank, and ash content (<15%), were shown to be minor considerations.

The following observations regarding the flow properties of coal are relevant:

- Coal displays significant strength even under instantaneous conditions. This strength increases dramatically with time of storage at rest, particularly at higher moisture contents.
- The strength of coal, as indicated by the flow function, displays maximal strength for moisture contents in the range of 10 - 15%. These moisture content levels represent the typical range of most handling operations, and are significantly less than the saturation moisture content.
- The instantaneous and time flow function have geometrically similar gradients at low consolidation stresses.
- The effective angle of internal friction displays a decreasing variation with increasing consolidation stress for moist coal. The
average value of $\delta$ increases with increasing moisture content, typically $45^\circ$ for air dried and $50 - 55^\circ$ at $6\%$ levels, to $60^\circ-70^\circ$ for $10\%$ and $15\%$ moisture contents.

- Significant variations were displayed in the wall friction coefficients for different wall lining materials. At low consolidation stresses, moist coal displays a rapid decrease in the kinematic angle of wall friction with increasing $\sigma_1$. This feature is attributable to adhesion of the moist coal to some surfaces, for example 304-2B stainless steel. Variable angles of wall friction were also displayed for those materials that have convex upward wall yield loci.

- The maximum bulk density values were determined for air dried and $15\%$ moisture content samples. For intermediate moisture levels bulk density values decreased from those determined for the air dried level. The bulk density variation increases asymptotically to limiting values of $1000 \text{ kg/m}^3$ and $1075\text{ kg/m}^3$ for $10\%$ and $15\%$ moisture contents respectively.

Flow property tests were conducted on samples prepared at $-1.00\text{mm}$, $-2.36\text{mm}$ and $-4.00\text{mm}$. Comparison of the $-2.36\text{mm}$ and $-4.00\text{mm}$ sample results are similar for the various flow properties, and does not indicate any less conservative results for the $-4.00\text{mm}$ samples. The $-1.00\text{mm}$ test sample results displayed significantly greater stronger flow functions with more scatter compared to the other two samples. The combined action of fine particle distribution and high moisture content substantially reduces the handleability of coal. Shear tests on $-1.00\text{mm}$ at $10\%$ and $15\%$ moisture contents indicate $\sigma_c$ values of up to twice the values determined for the two larger particle cut test samples.

The flow properties of coal samples mixed with Kaolin and Bentonite clays (to simulate high ash content coals) were determined and
display similar results to those of high fines content coals. The major feature of the clay sample flow properties was the extremely strong time flow functions, which often displayed a cementing action. In addition to displaying the adverse flow properties for high clay content coals, these results also highlight the effect of a high fines content in reducing the coal handleability. This situation can occur for soft friable coals which degrade easily during handling operations. The higher fines content then leads to higher moisture retention capabilities and a consequent deterioration of the handleability characteristics.

8.2 DESIGN PROCEDURES FOR THE DETERMINATION OF MASS FLOW HOPPER GEOMETRY PARAMETERS

Manual and computer aided design approaches for the determination of mass flow hopper geometry parameters were considered in this work.

Chapter 4 presents the development of an alternative presentation of the original Jenike flow factor charts, for the display of the design parameters for mass flow hoppers. These alternative charts present only the critical design values of flow factor and $\alpha$ in the border region between mass flow and funnel flow for axisymmetric and plane flow hoppers.

The charts eliminate the need for imprecise parameter interpolations (necessary with Jenike flow factor charts) by displaying the required design parameters of $\text{ff}$ and $\alpha$ as a function of the effective angle of internal friction and kinematic angle of wall friction. This format also provides an overall assessment of the variation of $\text{ff}$ and $\alpha$ along the mass flow design limits, and the sensitivity of these two parameters with $\delta$ and $\phi$ values.
The alternative presentation of the hopper design parameters has been utilised in the development of graphical nomograms or *worksheets* for the manual determination of $\alpha$ and $B$. Utilising this presentation of hopper design data, where all parameters are displayed as a function of a common independent variable, $\sigma_1$, the following aspects are clearly detailed:

- the relation between hopper outlet dimension and $\sigma_1$.
- the correlation of $\phi$ with the respective values of wall slope.
- the sensitivity of the flow function position on values of $B$. This is important for low values of the critical design point, where $\sigma_1$ may be remote from the experimental data points used to determine the flow function.

The critical hopper geometry design point is determined by the intersection between the flow factor locus and the respective flow function. An important feature of the flow factor locus is the lower end point, which specifies the lower limit of $\sigma_1$ for which a ff and hence a critical hopper geometry can be determined. The lower limit is determined for a particular hopper shape, on the basis of $\phi$ and $\delta$, has typical values of $2.5 < \sigma_1 < 3.5$ kPa for coals at 10% and 15% moisture content with 304-2B stainless steel.

The usefulness of the graphical nomogram is further demonstrated when the values of $\alpha$ and $B$ are required to satisfy additional design constraints. Typical constraints involved in the detailing of the hopper geometry includes allowable headroom, maximum lump size, feeder arrangements and proposed discharge flow rates. These constraints can be added to the nomogram to highlight those regions which satisfy the design objectives.

The nomogram presentation also highlights the significant influence of $\phi$, and the minor effect of $\delta$ in generating the $\alpha$ versus $\sigma_1$ and $B$ versus $\sigma_1$ design curves. These features can be utilised by the designer for
hoppers where the value of B is known to be greater than the critical (based on experience or previous hopper designs). For this situation the flow function need not be known and the hopper design can be based on the wall friction and compressibility tests only. This advantage of this approach is that both of these laboratory tests are quite straightforward and fast, without the need for shear testing using the sophisticated equipment and procedures involved with the Jenike-type Direct Shear Tester.

Chapter 6 presents the development of standardised hopper design guidelines, based on the results of the flow property testing program and the Jenike hopper design procedures. The guidelines apply to hard black coals, similar to those tested, namely, a rank of sub-bituminous to semi-anthracite, an ash content less than 15%, HGI < 60, and 304-2B stainless steel as the hopper wall lining material.

Two approaches are presented. The first, specifies the expected values of \( \alpha \) and B (under instantaneous and time storage conditions) by analysing statistically the hopper geometry parameter results presented in Appendix H, by the *Students' t Distribution*. The expected values are then expressed as the mean value within a 90% confidence interval.

For example, the expected geometry parameter ranges for 10% moisture content coal are \( \alpha_c: 20.5^\circ < \alpha_c < 22.5^\circ, \alpha_p: 30.0^\circ < \alpha_p < 32.0^\circ, B_c: 950 < B_c < 1170\text{mm} \) and \( B_p: 435 < B_p < 535\text{mm} \). This information is useful for providing values required for preliminary engineering layouts or for reviewing existing coal bins that are experiencing storage problems.

The second approach considers the mean and range of the various flow property values, and the respective range of flow factors relevant to the determination of the critical hopper design. This analysis allows values of \( \alpha \) and B to be estimated from a reduced flow property testing program. Tests are required only to determine or confirm these property values which
exert significant influence on α and B, while for those properties that have a minor effect, (such as δ), expected values displayed on graphs for various moisture contents can be used.

To provide an estimate of $\bar{\sigma}_1$, for the calculation of the outlet dimension B, this second approach requires the determination of one yield locus, to provide a reference point for the flow function. The value of $\bar{\sigma}_1$ at the critical design point can be estimated by projecting the flow function (passing through $(\sigma_1, \sigma_\varepsilon)$ with a slope parallel to the graphically presented mean flow function) and intersecting with the mean flow factor range.

Selection of the consolidation level of the shear test is required to ensure the coordinate $(\sigma_1, \sigma_\varepsilon)$ determined lies within the $\sigma_1$ range specified for each moisture content. Errors in estimation of $\bar{\sigma}_1$ can occur if this coordinate is far outside these ranges.

The procedure emphasises the need to know the kinematic angle of wall friction variation for proposed materials and the bulk density variation for mass flow hopper design. This approach extends on the last aspect discussed regarding the graphical nomogram, by providing expected flow property and flow factor trends close to the critical design point for hopper designs.

Chapter 7 provides details of two computer programs, $FP$ and $BD$, which process and analyse experimental flow property data, and determine the mass flow hopper geometry parameters respectively. Utilisation of these programs have demonstrated substantial benefits in time savings and increased consistency and sophistication of the procedures over manual methods. Both programs have been developed to operate on a two monitor microcomputer system utilising an iterative graphical format.
The program $FP$, processes the experimental flow properties and presents them graphically and by characteristic empirical equations. These equations have proved a convenient and accurate method of specifying the flow properties for input into other materials handling computer programs. The three parameter equation used to describe some of the flow properties has proved to be most versatile.

Program $BD$ determines the critical mass flow hopper geometry based on the empirical equations specifying the various flow properties. In addition to determining the critical values of $\alpha$ and $B$, the program calculates the variation of $\alpha$ with $B$ for values greater than the critical. This design graph has proved useful for the design of hoppers where the proposed wall lining material has a variable kinematic angle of wall friction and increased values of $\alpha$ utilised for increased values of $B$.

For determination of the critical design point, the program incorporates the flow factor locus approach (utilised in the graphical nomograms). This allows a direct and straightforward computer algorithm to be implemented, where the existence of, and values of hopper wall slope and outlet span can be found by comparing the relevant flow function with the flow factor locus.

### 8.3 Future Research Directions

Several topics requiring further research have been identified during the course of this work. The coal flow property testing program highlighted the following aspects:

- Investigation of the relation between the surface moisture content for the complete coal distribution and the $-4.00\text{mm}$ (or $-2.36\text{mm}$) coal sample used for flow property testing. Clarification of the proportion of surface moisture existing with the fines
portion (0 x -4.00mm) of the complete coal would allow the preparation of test samples at the actual level.

Preparation of the sample at the correct moisture content would then reduce the degree of conservatism introduced into the flow property test results, particularly for the flow function.

- As highlighted in this work, the shear testing is now guided by a standardised procedure. The procedure utilises the prorating of instantaneous yield loci points suggested by Jenike [68,69]. There is a need to extend this standard procedure to incorporate the testing of time yield loci. Generally it was found that greater scatter occurs with the time yield loci data than with the instantaneous points. A prorating procedure proposed by Jenike [68], was applied to experimental data in preliminary tests, however little reduction in the scatter of time yield loci data occurred.

Relevant to the hopper design procedures, accurate determination of the time flow function is important, as this is often the limiting property for the calculation of the critical outlet dimension.

- The second flow property test that requires standardisation is the Coulomb friction test for determination of the wall friction angles. Chapters 5 and 6 highlight the importance of this parameter in mass flow hopper design. It is therefore important that this procedure be standardised to provide increased consistency in measuring the wall yield locus and an indication of the $\phi$ variation that can be expected.
Currently slightly different wall yield loci results can be obtained by either increasing or decreasing the consolidation weights during the test, or using different weight increments.

Chapter 6 has detailed the development of standardised hopper design guidelines. The development should be continued to increase the number of data values statistically analysed, and to incorporate hopper geometry design parameters determined for other coals from different coalfields (but which satisfy the stated terms of reference).

The guidelines should be extended to include data on other wall lining materials. In recent times other wall lining materials such as 3CR12 and 301 stainless steel commonly have been specified for application in coal storage facilities.

The further development of computer software for bin design, specifically configured for microcomputers is a worthwhile direction. The structure of the program BD has been arranged conveniently to incorporate additional design modules. Suggested future modules include funnel flow bin design, feeder load predictions, bin wall load predictions and bin volume/overall dimension design graphs for the preliminary planning and sizing of storage facilities.

Recent developments in computer software incorporating artificial intelligence offer a longer term research goal for the application of computer aided design techniques to the design of bulk solid storage facilities. Interpretation of the flow properties and hopper geometry parameter design data in designing a cost efficient installation that satisfies various constraints requires significant expertise and experience.

Development of a knowledge based expert system combining the expertise of a specialist with the relevant technical engineering data
(including hopper geometry parameters, bulk material characteristics, standard feeder arrangements and site details) for the design and detailing of storage bins would be an extremely useful facility.
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APPENDIX A

STANDARDISED PROCEDURE FOR SHEAR TESTING.

A.1 INTRODUCTION

The procedure presented in the following sections, although developed for the experimental shear testing of hard black coal is generally applicable to other granular bulk solids. The main steps involved in the procedure are the preparation of the test sample, the determination of the yield loci at various consolidation levels and the interpretation of these results to derive the flow function.

Features that are highlighted for the determination of the instantaneous yield loci include determination of the cell loading at pre-consolidation from an under-consolidated state, plotting the yield data points as obtained to ensure their validity and the use of a prorating technique to reduce scatter of these data points in defining the yield locus position.

A.2 SAMPLE PREPARATION

A sample of the bulk solid to be examined should be air-dried and a -4.00mm cut taken to provide a sub-sample of at least 1kg in size. Alternatively wet-sieving techniques can be used to provide the sample without the need for air-drying. This approach has advantages in minimising the alteration of the fines particle distribution due to the tendency of particles to agglomerate and be removed during sieving.

The moisture content of the sample should be measured before and after testing in accordance with AS 1038, Part 1, Method C [70] and should not vary by more than 0.5% on a mass basis over the testing period.
A.3 EQUIPMENT REQUIRED

- A Jenike-type, Direct Shear tester with Chart recorder.
- A 95.3mm (3-3/4 inch) inside diameter shear cell of standard dimensions.
- Twisting lid, shear lid and moulding ring for above cell.
- Twisting wrench.
- Weight carrier and appropriate weights.
- Spoon, scraper and brush.

A.4 TEST PROCEDURES FOR DETERMINING INSTANTANEOUS YIELD LOCI

The procedure for determining the points on an individual instantaneous yield loci has three stages:

(i) Pre-consolidation of the sample
(ii) Consolidation of the sample under shear
(iii) Shear of the sample.

Each of these stages of the procedure are considered in detail below.

A.4.1 Pre-consolidation of the Sample

Place the cell base, shear ring and mould ring on the Shear Tester, Figure A.1. Adjust the offset of the shear ring to approximately 3mm. The 3mm represents the traversing distance of upper shear cell ring

Pack a sample of the material to be tested into the shear cell, layer by layer, each layer being spread lightly and uniformly with a spoon or the fingers. Care must taken to ensure that no smooth or regular surfaces are formed which may create a preferential shear during testing. Scrape off
Figure A.1: Jenike Shear Cell Setup for Pre-consolidation.
excess material level with the top of the mould ring. Cover the sample with the twisting lid.

Apply a normal vertical force $V_{tl}$ to the twisting lid by means of a weight carrier, and, by using the special twisting wrench, apply a number of oscillating twists (amplitude approximately $\pm 20^\circ$) to the lid. During this procedure care should be taken not to press down on the twisting lid and not to impede the motion of the shear ring as it tends to follow the motion of the twisting lid.

The selection of the value of $V_{tl}$ and the number of twists to be applied is determined by trial and error. For most dry samples $V_{tl}$ is made equal to $V$, the normal force used in the consolidation-under-shear procedure described below. However, for high moisture samples, values of $V_{tl}$ equal to 2 to 3 times $V$ may be required. The number of complete twists applied initially is about 20. The number of twists can be increased to approximately 40, although this may increase the chance of disturbing the cell. Altering the number of twists can be considered a method of fine adjustment rather than altering the value of $V_{tl}$.

- Remove weight carrier from the twisting lid.
- Lift off mould ring while holding down twisting lid and shear ring.
- Slide the twisting lid off and scrape the excess material flush with the top off the shear ring. In these operations care should be taken to avoid any movement of the shear ring. Clean away excess material with the brush and be sure that the lid is placed on sample container to limit moisture loss from the sample. The lid should not be removed by direct lifting because adhesion of the coal (particularly at high moisture contents) usually leads to destruction of the cell compact.
A.4.2 Consolidation under Shear

Consolidation of the sample is completed by a shearing operation which causes the material to flow under the consolidating stresses until a steady state shear value is reached or closely approached. This is performed as follows:

- Place the shear lid on the sample taking care to centre it within the shear ring.
- Apply the force $V_b$ to the lid, using an appropriate weight, and advance the stem of the Direct Shear Tester against the bracket, Figure A.2.
- Let shearing proceed until a condition is reached when a layer of the material across the whole sample is caused to flow plastically indicated by the recorded shear force reaching a steady value $S$. Ideally, this steady value of shear force should be reached when the shear ring is concentric with the base of the cell because of the limited travel of the cell arrangement.
- Reverse the stem travel until the shear force drops to zero. Then remove the force $V_t$.

It is important that the steady state shear force $S$ is reached as indicated by curve B, Figure A.3; the sample is then said to be critically consolidated. If the shear force continues to rise for the complete stem travel, curve A in Figure A.3, then the sample was under consolidated during the pre-consolidation phase. Generally, this means that an increase is needed in the pre-consolidation force $V_t$ and/or the number of twists used. If the shear force reaches a maximum then reduces, curve C in Figure A.3, the sample was over consolidated during the pre-consolidation phase. Generally, this means that the value of $V_t$ and/or the number of twists was excessive.
Figure A.2: Jenike Shear Cell Setup for Consolidation.

Figure A.3: Types of Shear Consolidation Curves.
A note of caution should be sounded here. The trial and error procedure (for selecting $V_j$ and number of twists) should approach the critically consolidated state from a condition of under rather than over consolidation. Otherwise it is tempting to over consolidate the sample and stop the shear consolidation procedure at point X on Curve C in Figure A.3. Such samples are not critically consolidated and can lead to considerable error in the resulting yield loci.

A.4.3 Shear of the Sample

The third stage of the test is the actual shearing of the sample under force $\bar{V}_j$, smaller than $V$. The following is used:

- Apply force $V_{bi}$ to the shear lid, using an appropriate weight.
- Advance the stem of the machine until it almost touches the bracket.
- Let shearing proceed until the recorded pen reaches and passes a maximum value, $\bar{S}_i$.
- Retract stem and remove force $V_{bi}$.
- Remove the entire cell including the shear lid and split the shear ring and base apart. Check to see that the shear plane is between the ring and the base and not angled up or down striking the lid or bottom of the cell. If this has happened the complete test must be repeated.

Determine the additional vertical force, $V_a$ above the shear plane. $V_a$ is the vertical force due to:

(i) shear lid.

(ii) shear ring.

(iii) mass of material contained within the ring.
This determination only needs to be done occasionally for each level of consolidation.

A.4.4 Determining the Complete Family of Yield Loci

The entire three stage procedure is repeated two more times for the same level of consolidation, applying the force \( V_b \) to the shear lid during shear consolidation but applying forces \( V_{b_2} \) and \( V_{b_3} \) to the lid during shear. A fresh sample of material is used for each test. This set of results will be used to provide one complete yield locus.

A complete series of tests needs to be performed at two other levels of consolidation, one higher and one lower than the first level. Thus the minimum number of valid tests which must be performed to obtain the family of instantaneous yield loci is nine.

As an example, presented in Table A.1 for a coal at 10% total moisture content are the suggested forces to apply to the shear lid. The force levels presented may have to be varied slightly to suit particular conditions and to enable a complete set of valid test results to be obtained. Figure A.4 shows the range of valid points for a yield locus.

It is absolutely essential that the test values are plotted as the tests proceed to indicate that valid test points are being obtained. Reference is also made between the yield loci of different yield loci in developing the family concept and increasing the confidence of the result, and selecting values for the next test cell.
First Series of Tests - Medium Consolidation Level

Shear Consolidation  \( V_b = 22.6 \text{ N (2.3kg)} \)
Sample Shear  \( V_{b_1} = 12.8 \text{ N (1.3kg)} \)
\( V_{b_2} = 8.8 \text{ N (0.9kg)} \)
\( V_{b_3} = 3.9 \text{ N (0.4kg)} \)

Second Series of Tests - High Consolidation Level

Shear Consolidation  \( V_b = 31.4 \text{ N (3.2kg)} \)
Sample Shear  \( V_{b_1} = 17.7 \text{ N (1.8kg)} \)
\( V_{b_2} = 12.8 \text{ N (1.3kg)} \)
\( V_{b_3} = 7.8 \text{ N (0.8kg)} \)

Third Series of Tests - Low Consolidation Level

Shear Consolidation  \( V_b = 13.7 \text{ N (1.4kg)} \)
Sample Shear  \( V_{b_1} = 6.9 \text{ N (0.7kg)} \)
\( V_{b_2} = 4.9 \text{ N (0.5kg)} \)
\( V_{b_3} = 2.9 \text{ N (0.3kg)} \)

Table A.1: Suggested Forces for Shear Testing of Coal
Figure A.4: Valid Range Points for Instantaneous Yield Locus.
A.5 PLOTTING TEST RESULTS TO DETERMINE INSTANTANEOUS YIELD LOCI

When determining a family of yield loci, such as shown in Figure A.5, it is important that certain fundamental principles be observed when interpreting the test results.

These can be summarised as follows:

- ensure that the samples have been critically consolidated.
- loci should be drawn as straight lines.
- loci should be parallel or fan out slightly as the normal load (or stress) increases.
- loci must not intersect.
- the shear consolidation point does not necessarily correspond to the end point of the yield locus.
- the shear consolidation points generally lie close to a straight line which either passes through or above the origin.
- the force due to the weight of the shear lid, shear ring and material contained in the shear ring \( V_A \) must be added to all vertical forces applied to the shear cover \( V_B \) and \( V_{bi} \) to give the total vertical or normal force applied to the shear plane.
- the smoothing or prorating procedure of Jenike works well for instantaneous yield locus test shear force results.
- the yield loci data must fall within the valid range defined in Figure A.4 and only vary within defined bounds.
- the yield loci can either be plotted in force or stress units. For convenience it is recommended that force units be used.
Figure A.5: An Example of a Family of Instantaneous Yield Loci.
A.5.1 Prorating Procedure

When determining a yield locus, the value of shear force $S$ obtained during the shear consolidation process will usually show some scatter. The allowable deviation of $S$ from the intermediate value should be less than ±5% and the following relationship [68,69] should be used to adjust or prorate the raw test results.

\[
(S_i)_{\text{prorated}} = \frac{(S_i)_{\text{test}} \times S_{\text{selected}}}{S_{\text{test}}}
\]  

(A.1)

The value of $S_{\text{selected}}$ should be an intermediate value within the range of scatter of the $S_{\text{test}}$ values; an average value of all the $S_{\text{test}}$ values may be satisfactory. As a guide, when prorating $(S_i)_{\text{test}}$ values for a family of yield loci, the $S_{\text{selected}}$ values should lie close to a straight line which passes through or just above the origin.

A.5.2 Example of Prorating Procedure

The data tabulated in Table A.2 represents a series of yield locus raw test results for 10% moisture content coal and their subsequent prorating. The resulting plots of the yield loci ($V$, $S_{\text{selected}}$) and ($\bar{V}_i$, $(\bar{S}_i)_{\text{prorated}}$ values for each level of consolidation) are plotted in Figure A.5.

A.6 DETERMINING THE INSTANTANEOUS FLOW FUNCTION

Once the yield loci have been plotted Mohr stress circles can be drawn for each locus as follows, Figure A.5:

- draw a semicircle, centred on the Normal Force axis, to pass through the point $V$, $S_{\text{selected}}$ (marked X) and be tangent to the yield locus. This is referred to as the Mohr circle of flow and describes the consolidation condition for the locus.
• draw a semicircle, centred on the Normal Force axis, to pass through the origin and be tangent to the yield locus. This is referred to as the Unconfined Mohr circle and describes the unconfined strength of the bulk solid for the consolidation level of the yield locus.

Note that since circles are being drawn on the IYL graph it is implied that the same scale has been used for the horizontal and vertical axes.

These Mohr circles provide three combinations of Major Consolidation Force, \( V_1 \) and Unconfined Yield Force, \( F \), for the three members of the yield loci family previously determined. For the example given in the previous section and the corresponding yield loci plotted in Figure A.5, these values are presented in Table A.3. These forces can be converted to stresses by dividing by the cross-sectional area of the shear cell. This area is \( \frac{1}{140} \, \text{m}^2 \) for the 95.3mm diameter cell.

This conversion changes
\[
V_1 \Rightarrow \sigma_1 \, \text{(major consolidation stress)}
\]
\[
F \Rightarrow \sigma_c \, \text{(unconfined yield stress)}
\]

and the corresponding values of the example are presented in Table A.4. These values are plotted in Figure A.6 to provide the Instantaneous Flow Function. This then quantifies the flow properties of the material as relevant to short periods of storage.

Generally, the Instantaneous Flow Function can be drawn as a straight line of best fit through the three plotted points. Alternatively, a convex upward curve may be drawn. The flow function when extended should pass through or above the origin of the graph. It will be noted that the same scale must be used for the horizontal and vertical axes.
<table>
<thead>
<tr>
<th>Medium Consolidation</th>
<th>Test No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
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</thead>
<tbody>
<tr>
<td>$V_b$</td>
<td>22.6</td>
<td>22.6</td>
<td>22.6</td>
<td></td>
</tr>
<tr>
<td>$V_a$</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>$V = V_b + V_a$</td>
<td>26.2</td>
<td>26.2</td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>24.5</td>
<td>26.0</td>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td>$S_{selected}$</td>
<td>12.8</td>
<td>8.8</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>$\tilde{V}<em>i = V</em>{bi} + V_a$</td>
<td>16.4</td>
<td>12.4</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>$(\tilde{S}_i)^{test}$</td>
<td>19.4</td>
<td>17.3</td>
<td>11.7</td>
<td></td>
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<tr>
<td>$(\tilde{S}_i)^{prorated}$</td>
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<td>16.3</td>
<td>12.5</td>
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<table>
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<th>5</th>
<th>6</th>
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<td>31.4</td>
<td>31.4</td>
<td>31.4</td>
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</tr>
<tr>
<td>$V_a$</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>$V = V_b + V_a$</td>
<td>35.2</td>
<td>35.2</td>
<td>35.2</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>33.5</td>
<td>34.0</td>
<td>32.0</td>
<td></td>
</tr>
<tr>
<td>$S_{selected}$</td>
<td>17.7</td>
<td>13.8</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>$\tilde{V}<em>i = V</em>{bi} + V_a$</td>
<td>21.5</td>
<td>16.6</td>
<td>11.6</td>
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<tr>
<td>$(\tilde{S}_i)^{test}$</td>
<td>25.9</td>
<td>22.3</td>
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<td>$(\tilde{S}_i)^{prorated}$</td>
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<th>Test No.</th>
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<th>8</th>
<th>9</th>
</tr>
</thead>
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<td>13.7</td>
<td>13.7</td>
<td>13.7</td>
<td></td>
</tr>
<tr>
<td>$V_a$</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>$V = V_b + V_a$</td>
<td>17.1</td>
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<td>17.1</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>15.8</td>
<td>16.9</td>
<td>15.7</td>
<td></td>
</tr>
<tr>
<td>$S_{selected}$</td>
<td>6.9</td>
<td>4.9</td>
<td>2.9</td>
<td></td>
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<tr>
<td>$\tilde{V}<em>i = V</em>{bi} + V_a$</td>
<td>10.3</td>
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<tr>
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<td>12.3</td>
<td>11.6</td>
<td>9.3</td>
<td></td>
</tr>
</tbody>
</table>

**Table A.2:**  Example of Raw Test Data for Yield Loci at Three Consolidation Levels, and Final Prorated Values.(All Forces in Newtons).
### Table A.3: Coordinates of Three Yield Loci Defining the Instantaneous Flow Function of the Example (Force Units).

<table>
<thead>
<tr>
<th>Consolidation Level</th>
<th>$V_1$</th>
<th>$F$</th>
</tr>
</thead>
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<tr>
<td>High Consolidation</td>
<td>78.9</td>
<td>35.2</td>
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<tr>
<td>Medium Consolidation</td>
<td>58.2</td>
<td>27.9</td>
</tr>
<tr>
<td>Low Consolidation</td>
<td>37.6</td>
<td>19.1</td>
</tr>
</tbody>
</table>

### Table A.4: Coordinates of Three Yield Loci Defining the Instantaneous Flow Function of the Example (Stress Units)

<table>
<thead>
<tr>
<th>Consolidation Level</th>
<th>$\sigma_1$</th>
<th>$\sigma_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Consolidation</td>
<td>11.0</td>
<td>4.9</td>
</tr>
<tr>
<td>Medium Consolidation</td>
<td>8.1</td>
<td>3.8</td>
</tr>
<tr>
<td>Low Consolidation</td>
<td>5.3</td>
<td>2.7</td>
</tr>
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</table>

Table A.3: Coordinates of Three Yield Loci Defining the Instantaneous Flow Function of the Example (Force Units).

Table A.4: Coordinates of Three Yield Loci Defining the Instantaneous Flow Function of the Example (Stress Units)
Figure A.6: An Example of an Instantaneous Flow Function.

Unconfined Yield Stress - Kilopascals

Major Consolidation Stress - Kilopascals

Flow Function

Material: Washed Coal
Moisture Content: 10% WB

Tested: Oct., 1982
Temperature: Ambient
APPENDIX B

FLOW PROPERTY TEST SAMPLE PARTICLE DISTRIBUTIONS
**Rosin-Rammler Cumulative Size Distribution**

Material: Coalcliff Rom Coal as Rec'd

Moisture Content: Air Dried

Tested: 1984

Temperature: Ambient

**Figure 8.1**

---

**Rosin-Rammler Cumulative Size Distribution**

Material: Coalcliff Rom Coal -2.36MM

Moisture Content: Air Dried

Tested: 1984

Temperature: Ambient

**Figure 8.2**
SIEVE APERTURE -

PERCENTAGE MASS UNDERSIZE

PERCENTAGE MASS OVERSIZE

ROSSIN-ROMMLER CUMULATIVE SIZE DISTRIBUTION

MATERIAL: SOUTH BULLI PROD. COAL AS REC'D TESTED: 1984
MOISTURE CONTENT: AIR DRIED
TEMPERATURE: AMBIENT

FIGURE: B.3

ROSSIN-ROMMLER CUMULATIVE SIZE DISTRIBUTION

MATERIAL: SOUTH BULLI PROD. COAL -2.38MM TESTED: 1984
MOISTURE CONTENT: AIR DRIED
TEMPERATURE: AMBIENT

FIGURE: B.4
ROsin-RAMMLeR CUMULATIVE SIZE DISTRIBUTION
MATERIAL: HUNTrLEY ROM COAL AS Rec'D   TESTED: 1984
MOISTURE CONTENT: AIR DRIED   TEMPERATURE: AMBIENT

Figure: B.5

ROsin-RAMMLeR CUMULATIVE SIZE DISTRIBUTION
MATERIAL: HUNTrLEY ROM COAL -2.36MM   TESTED: 1984
MOISTURE CONTENT: AIR DRIED   TEMPERATURE: AMBIENT

Figure: B.6
ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION
MATERIAL: METROPOLITAN ROM COAL -1.00MM TESTED: 1984
MOISTURE CONTENT: AIR DRIED TEMPERATURE: AMBIENT

FIGURE: B.7

ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION
MATERIAL: METROPOLITAN ROM COAL -1.00MM TESTED: 1984
MOISTURE CONTENT: AIR DRIED TEMPERATURE: AMBIENT

FIGURE: B.8
ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION

MATERIAL: METROPOLITAN ROM COAL - 2.38MM TESTED: 1984
MOISTURE CONTENT: AIR DRIED TEMPERATURE: AMBIENT

FIGURE: B.9
Rosin-Rammler Cumulative Size Distribution

Material: Appin ROM Coal - 2.95mm
Moisture Content: Air Dried
Tested: 1984
Temperature: Ambient

Figure: B.13

Rosin-Rammler Cumulative Size Distribution

Material: Appin ROM Coal - 4.80mm
Moisture Content: Air Dried
Tested: 1984
Temperature: Ambient

Figure: B.14
ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION
MATERIAL: WESTCLIFF ROM COAL AS RECD  TESTED: 1984
MOISTURE CONTENT: AIR DRIED  TEMPERATURE: AMBIENT

FIGURE: B.15

ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION
MATERIAL: WESTCLIFF ROM COAL -1.08MM  TESTED: 1984
MOISTURE CONTENT: AIR DRIED  TEMPERATURE: AMBIENT

FIGURE: B.16
ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION

MATERIAL: WESTCLIFF ROM COAL -2.36MM
MOISTURE CONTENT: AIR DRIED
TESTED: 1984
TEMPERATURE: AMBIENT

FIGURE: B.17

ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION

MATERIAL: WESTCLIFF ROM COAL -4.00MM
MOISTURE CONTENT: AIR DRIED
TESTED: 1984
TEMPERATURE: AMBIENT

FIGURE: B.18
FIGURE B.21

ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION
MATERIAL: WESTCLIFF PROD. COAL -2.38MM TESTED: 1984
MOISTURE CONTENT: AIR DRIED TEMPERATURE: AMBIENT

FIGURE B.22

ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION
MATERIAL: WESTCLIFF PROD. COAL -4.00MM TESTED: 1984
MOISTURE CONTENT: AIR DRIED TEMPERATURE: AMBIENT
ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION

MATERIAL: WESTCLIFF COAL+FINES-CLAY COMP. TESTED: 1984
MOISTURE CONTENT: AIR DRIED  TEMPERATURE: AMBIENT

FIGURE: B.23

ROSIN-RAMMLER CUMULATIVE SIZE DISTRIBUTION

MATERIAL: WESTCLIFF COAL+FINES-CLAY COMP. TESTED: 1984
MOISTURE CONTENT: WET SIEVED  TEMPERATURE: AMBIENT

FIGURE: B.24
COMPARISON OF EXPERIMENTALLY DETERMINED FLOW PROPERTIES

APPENDIX C

INSTANTANEOUS AND TIME FLOW FUNCTION
Figure C.1 Comparison of Flow Functions for Coalcliff ROM Coal (-2.36mm)

Legend
1: Air Dried (Instantaneous)
2: 10% wb, (Instantaneous)
3: 15% wb, (Instantaneous)

Figure C.2 Comparison of Flow Functions for Coalcliff ROM Coal (15% wb)

Legend
1: -0.50mm Test Sample (Instantaneous)
2: -1.00mm Test Sample (Instantaneous)
3: -2.36mm Test Sample (Instantaneous)
Figure C.3 Comparison of Flow Functions for South Bulli Product Coal (-2.36mm)

Figure C.4 Comparison of Flow Functions for Huntley ROM Coal (-2.36mm)
Figure C.5 Comparison of Flow Functions for Metropolitan ROM Coal (-1.00 mm)

Figure C.6 Comparison of Flow Functions for Metropolitan ROM Coal (-2.36 mm)
Figure C.7 Comparison of Flow Functions for Metropolitan ROM Coal (-4.00mm)

Legend
1: Air Dried
2: 6%wb, Instantaneous
3: 6%wb, Time (3 Days)
4: 10%wb, Instantaneous
5: 15%wb, Time (3 Days)
6: 15%wb, Instantaneous
7: 15%wb, Time (3 Days)

Figure C.8 Comparison of Flow Functions for Appin ROM Coal (-1.00mm)

Legend
1: Air Dried
2: 6%wb, Instantaneous
3: 6%wb, Time (3 Days)
4: 10%wb, Instantaneous
5: 10%wb, Time (3 Days)
6: 15%wb, Instantaneous
7: 15%wb, Time (3 Days)
Figure C.9 Comparison of Flow Functions for Appin ROM Coal (-2.36mm)

Figure C.10 Comparison of Flow Functions for Appin ROM Coal (-4.00mm)
Figure C.11 Comparison of Flow Functions for Westcliff ROM Coal (-0.0mm)

Figure C.12 Comparison of Flow Functions for Westcliff ROM Coal (-2.36mm)
Figure C.13 Comparison of Flow Functions for Westcliff ROM Coal (-4.00mm)

Legend
1: Air Dried
2: 6\%wb, Instantaneous
3: 6\%wb, Time (3 Days)
4: 10\%wb, Instantaneous
5: 10\%wb, Time (3 Days)
6: 15\%wb, Instantaneous
7: 15\%wb, Time (3 Days)

Figure C.14 Comparison of Flow Functions for Westcliff Product Coal (-0.50mm)
Figure C.15 Comparison of Flow Functions for Westcliff Product Coal (-1.00mm)

Legend
1: 6%wb, Instantaneous
2: 6%wb, Time (3 Days)
3: 10%wb, Instantaneous
4: 10%wb, Time (3 Days)
5: 15%wb, Instantaneous
6: 15%wb, Time (3 Days)

Figure C.16 Comparison of Flow Functions for Westcliff Product Coal (-2.36mm)

Legend
1: 6%wb, Instantaneous
2: 6%wb, Time (3 Days)
3: 10%wb, Instantaneous
4: 10%wb, Time (3 Days)
5: 15%wb, Instantaneous
6: 15%wb, Time (3 Days)
Figure C.17 Comparison of Flow Functions for Westcliff Product Coal (-4.00mm)

Figure C.18 Comparison of Flow Functions for Westcliff Product Coal (10% wb.)
Figure C.19 Comparison of Flow Functions for Westcliff Product Coal (15% wb)

Legend
1: 50mm Test Sample (Instantaneous)
2: 1.00mm Test Sample (Instantaneous)
3: 2.36mm Test Sample (Instantaneous)
4: 4.00mm Test Sample (Instantaneous)

Figure C.20 Comparison of Flow Functions for Westcliff ROM Coal (Tumbled 1 1/2 hours and Remixed -2.36mm)

Legend
1: 10wb, (Control) Instantaneous
2: 10wb, (Control) Time (3 Days)
3: 15wb, (Control) Instantaneous
4: 15wb, (Control) Time (3 Days)
5: 10wb, (Tumbled), Instantaneous
6: 10wb, (Tumbled), Time (3 Days)
7: 15wb, (Tumbled), Instantaneous
8: 15wb, (Tumbled), Time (3 Days)
Figure C.21 Comparison of Flow Functions for Various Coals (-2.36mm, 10%wb)

Figure C.22 Comparison of Flow Functions for Various Coals (-2.36mm, 15%wb)
Figure C.23 Comparison of Flow Functions for Various Coals (10% wb., -2.36mm)

Figure C.24 Comparison of Flow Functions for Various Coals (15% wb., -2.36mm)
Figure C.25 Comparison of Flow Functions for Various Coals (-4.00mm, 10%wb)

Figure C.26 Comparison of Flow Functions for Various Coals (-4.00mm, 15%wb)
Figure C.27 Comparison of Flow Functions for Westcliff ROM Coal with Bentonite (4.00mm, Various Moisture Contents)

Figure C.28 Comparison of Flow Functions for Westcliff ROM Coal Samples from Free Clay Test Program (-4.00mm)
Figure C.29 Comparison of Flow Functions for Westcliff ROM Coal Without Free Clay (-4.00mm, Various Moisture Contents)

Legend
1: Westcliff ROM Coal (Control) 10% wb, Instantaneous
2: Westcliff ROM Coal (Control) 10% wb, Time (3 Days)
3: Westcliff ROM Coal (Control) 15% wb, Instantaneous
4: Westcliff ROM Coal (Control) 15% wb, Time (3 Days)
5: Westcliff ROM Coal + Fines 5% wb, Instantaneous
6: Westcliff ROM Coal + Fines 5% wb, Time (3 Days)
7: Westcliff ROM Coal + Fines 10% wb, Instantaneous
8: Westcliff ROM Coal + Fines 10% wb, Time (3 Days)
9: Westcliff ROM Coal + Fines 12.5% wb, Instantaneous
10: Westcliff ROM Coal + Fines 12.5% wb, Time (3 Days)
11: Westcliff ROM Coal + Fines 15% wb, Instantaneous
12: Westcliff ROM Coal + Fines 15% wb, Time (3 Days)
13: Westcliff ROM Coal (Control) 11% wb, Instantaneous

Figure C.30 Comparison of Flow Functions for Westcliff ROM Coal with Kaolin (-4.00mm, Various Moisture Contents)

Legend
1: 5% wb, Instantaneous
2: 5% wb, Time (3 Days)
3: 10% wb, Instantaneous
4: 10% wb, Time (3 Days)
5: 11% wb, Instantaneous (Preliminary Test)
6: 12% wb, Instantaneous
7: 12% wb, Time (3 Days)
APPENDIX D

EFFECTIVE ANGLE OF INTERNAL FRICTION
Figure D.1 Comparison of $\delta$ for Various Coals (-2.36mm, 10% wb)

Figure D.2 Comparison of $\delta$ for Various Coals (-2.36mm, 15% wb)
Figure D.3 Comparison of $\delta$ for Various ROM Coals (-4.00mm, 10% and 15% wb)

Figure D.4 Variation of $\delta$ with Moisture Content (-2.36mm)
Figure D.5 Variation of δ with Moisture Content for Westcliff ROM Coal (-2.36mm)

Figure D.6 Variation of δ with Particle Top Size for Westcliff Product Coal (10% wb)
Figure D.7 Variation of $\delta$ with Particle Top Size for Westcliff Product Coal (15% wb)

Figure D.8 Variation of $\delta$ for Metropolitan ROM Coal with Particle Top Size (10% and 15% wb)
Figure D.9 Comparison of $\delta$ for Three Coals with Similar Particle Distributions (-2.36mm, 10% and 15% wb)

Figure D.10 Comparison of $\delta$ for Westcliff Coal Tumbled and Remixed (-2.36mm, 10% and 15% wb)
Figure D.11 Comparison of $\delta$ for Coal Samples from the Clay Testing Program (-4.00mm, 5% wb)

Figure D.12 Comparison of $\delta$ for Coal Samples from the Clay Testing Program (-4.00mm, 10% and 15% wb)
APPENDIX E

STATIC ANGLE OF INTERNAL FRICTION
Figure E.1 Comparison for Various Coals (-2.36mm, 10% wb)

Figure E.2 Variation of $\phi_t$ for Metropolitan ROM Coal with Particle Top Size (10% and 15% wb)
Figure E.3 Comparison for Various Coals (-2.36 mm, 15% wb)

Figure E.4 Comparison for Three ROM Coals (-4.00 mm, 10% and 15% wb)
Figure E.5 Variation of $\phi_t$ for Westcliff Product Coal with Particle Top Size (10% and 15% wb)

Figure E.6 Variation of $\phi_t$ for Appin and Westcliff ROM Coal with Moisture Content (-2.36mm)
Figure E.7 Variation of $\phi_t$ for Three Coals with Similar Particle Distributions (-2.36mm, 10% and 15%wb)

Figure E.8 Comparison of $\phi_t$ for Westcliff Coal Tumbled and Remixed (-2.36mm, 10% and 15%wb)
Figure E.9 Comparison of $\phi_t$ for Coal Samples from the Clay Testing Program (-4.00mm, 5%wb)

Figure E.10 Comparison of $\phi_t$ for Coal Samples from the Clay Testing Program (-4.00mm, 10% and 15%wb)
APPENDIX F

KINEMATIC ANGLE OF WALL FRICTION
**Figure F.1** Variation of $\phi$ for Various Coals (-2.36mm, 10%wb) on Rusty Mild Steel

**Figure F.2** Variation of $\phi$ for Various Coals (-2.36mm, 15%wb) on Rusty Mild Steel
Figure F.3 Variation of $\phi$ for Various Coals (-2.36mm, 10%wb) on 304-2B Stainless Steel

Figure F.4 Variation of $\phi$ for Various Coals (-2.36mm, 15%wb) on 304-2B Stainless Steel
Figure F.5 Variation of $\phi$ for Various Coals (-2.36mm, 10%wb) on Pactene

Figure F.6 Variation of $\phi$ for Various Coals (2.36mm, 15%wb) on Pactene
Figure F.7 Variation of $\phi$ for Appin ROM Coal (-2.36mm) at Various Moisture Contents on Rusty Mild Steel

Figure F.8 Variation of $\phi$ for Westcliff ROM Coal (-2.36mm) at Various Moisture Contents on Rusty Mild Steel
Figure F.9  Variation of \( \phi \) for Westcliff ROM Coal (-2.36mm) at Various Moisture Contents on 304-2B Stainless Steel

Figure F.10  Variation of \( \phi \) for Appin ROM Coal (-2.36mm) at Various Moisture Contents on 304-2B Stainless Steel
Figure F.11 Variation of $\phi$ for Westcliff ROM Coal (-2.36mm) at Various Moisture Contents on Pactene

Figure F.12 Variation of $\phi$ for Appin ROM Coal (-2.36mm) at Various Moisture Contents on Pactene
Figure F.13 Variation of $\phi$ for Westcliff Product Coal (10%wb) at Various Particle Top Sizes on Rusty Mild Steel

Figure F.14 Variation of $\phi$ for Westcliff Product Coal (15%wb) at Various Particle Top Sizes on Rusty Mild Steel
Figure F.15 Variation of $\phi$ for Westcliff Product Coal (10% wb) at Various Particle Top Sizes on Pactene

Figure F.16 Variation of $\phi$ for Westcliff Product Coal (15% wb) at Various Particle Top Sizes on Pactene
Figure F.17  Variation of $\phi$ for Westcliff Product Coal (10% wb) at Various Particle Top Sizes on 304-2B Stainless Steel

Figure F.18  Variation of $\phi$ for Westcliff Product Coal (15% wb) at Various Particle Top Sizes on 304-2B Stainless Steel
Figure F.19 Variation of $\phi$ for Three Coals with Similar Particle Distributions (-2.36mm, 10% and 15%wb) on Rusty Mild Steel.

Figure F.20 Variation of $\phi$ for Three Coals with Similar Particle Distributions (-2.36mm, 10% and 15%wb) on 304-2B Stainless Steel.
Figure F.21 Variation of $\phi$ for Three Coals with Similar Particle Distributions (-2.36mm, 10% and 15%wb) on Pactene

Figure F.22 Variation of $\phi$ for Westcliff ROM Coal, Tumbled and Remixed, (-2.36mm, 10% and 15%wb) on Pactene and 304-2B Stainless Steel
Figure F.23 Variation of $\phi$ for Westcliff ROM Coal, Control and Coal + Fines Samples from the Clay Testing Program (-4.00mm, 10% and 15%wb) on Rusty Mild Steel

Figure F.24 Variation of $\phi$ for Westcliff ROM Coal, Control and Coal + Fines Samples from the Clay Testing Program (-4.00mm, 10% and 15%wb) on 304-2B Stainless Steel
Figure F.25 Variation of $\phi$ for Westcliff ROM Coal, Control and Coal + Fines Samples from the Clay Testing Program (-4.00mm, 10% and 15%wb) on Pactene

Figure F.26 Variation of $\phi$ for Westcliff ROM Coal and Added Clays from the Clay Testing Program (-4.00mm, 10% and 15%wb) on Rusty Mild Steel
Figure F.27 Variation of $\phi$ for Westcliff ROM Coal and Added Clays from the Clay Testing Program (-4.00mm, 10% and 15%wb) on 304-2B Stainless Steel

Figure F.28 Variation of $\phi$ for Westcliff ROM Coal and Added Clays from the Clay Testing Program (-4.00mm, 10% and 15%wb) on Pactene
APPENDIX G

BULK DENSITY
Figure G.1 Comparison of Bulk Density Variations for Various Coals (-2.36mm, 10%wb)

Figure G.2 Comparison of Bulk Density Variations for Various Coals (-2.36mm, 15%wb)
Figure G.3 Comparison of Bulk Density Variations for Westcliff Product Coal (15% wb) at Various Particle Top Sizes

Figure G.4 Comparison of Bulk Density Variations for Westcliff Product Coal (10% wb) at Various Particle Top Sizes
Figure G.5 Comparison of Bulk Density Variations for Huntley ROM Coal (-2.36mm) at Various Moisture Contents

Figure G.6 Comparison of Bulk Density Variations for South Bulli Product Coal (-2.36mm) at Various Moisture Contents
Figure G.7 Comparison of Bulk Density Variations for Appin ROM Coal (-4.00mm) at Various Moisture Contents

Figure G.8 Comparison of Bulk Density Variations for Metropolitan ROM Coal (-4.00mm) at Various Moisture Contents
Figure G.9 Comparison of Bulk Density Variations for Three Coals at Similar Particle Distributions (-2.36mm, 10%wb)

Figure G.10 Comparison of Bulk Density Variations for Three Coals at Similar Particle Distributions (-2.36mm, 15%wb)
Figure G.11 Comparison of Bulk Density Variations for Westcliff ROM Coal, Tumbled and Remixed (-2.36mm, 10% and 15%wb)

Figure G.12 Comparison of Bulk Density Variations for Westcliff ROM Coal, Control and Coal + Fines Samples from the Clay Testing Program (-4.00mm) at Various Moisture Contents
Figure G.13 Comparison of Bulk Density Variations for Westcliff ROM Coal and Added Clays from the Clay Testing Program (-4.00mm, 10%wb)

Figure G.14 Comparison of Bulk Density Variations for Westcliff ROM Coal and Added Clays from the Clay Testing Program (-4.00mm, 15%wb)
APPENDIX H

SUMMARY OF CRITICAL MASS FLOW HOPPER GEOMETRY PARAMETERS

Table H.1: Summary of Mass Flow Hopper Geometry Parameters for Coalcliff ROM Coal, for Various Moisture Contents and Sample Particle Top Sizes

<table>
<thead>
<tr>
<th>Wall Material</th>
<th>Instantaneous Conditions</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\alpha_c$ (deg.)</td>
<td>$B_c$ (mm.)</td>
</tr>
<tr>
<td>-2.36mm Test Sample, Air Dried</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>4.0</td>
<td>25</td>
<td>14.0</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>4.5</td>
<td>25</td>
<td>15.0</td>
</tr>
<tr>
<td>Pactene</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>-2.36mm Test Sample, 10% w.b. Moisture Content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>21.0</td>
<td>870</td>
<td>30.0</td>
</tr>
<tr>
<td>Pactene</td>
<td>12.5</td>
<td>770</td>
<td>21.5</td>
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<td>-2.36mm Test Sample, 15% wb. Moisture Content</td>
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<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>8.5</td>
<td>870</td>
<td>17.5</td>
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<tr>
<td>304-2B Stainless Steel</td>
<td>22.0</td>
<td>1050</td>
<td>31.5</td>
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<td>Pactene</td>
<td>18.0</td>
<td>990</td>
<td>27.5</td>
</tr>
<tr>
<td>-1.00mm Test Sample, 15% wb. Moisture Content</td>
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<tr>
<td>Rusty Mild Steel</td>
<td>3.5</td>
<td>900</td>
<td>13.0</td>
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<td>304-2B Stainless Steel</td>
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<td>28.5</td>
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<tr>
<td>Pactene</td>
<td>11.0</td>
<td>1020</td>
<td>20.0</td>
</tr>
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</table>

* Critical Parameters are governed by wall friction considerations and particle interlocking rather than cohesive arching.
Table H.2: Summary of Mass Flow Hopper Geometry Parameters for South Bulli Product Coal (-2.36mm Test Sample).

<table>
<thead>
<tr>
<th>Wall Material</th>
<th>Instantaneous Conditions</th>
<th>TimeStorage Conditions (3Days)</th>
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<tbody>
<tr>
<td></td>
<td>$\alpha_c$</td>
<td>$B_c$</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>(mm.)</td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>*</td>
<td>8.5</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>1.5</td>
<td>110</td>
</tr>
<tr>
<td>Pactene</td>
<td>*</td>
<td>*</td>
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<tr>
<td>Air Dried</td>
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</tr>
<tr>
<td>6% w.b. Moisture Content</td>
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<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
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<tr>
<td>304-2B Stainless Steel</td>
<td>21.0</td>
<td>880</td>
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<td>Pactene</td>
<td>20.5</td>
<td>875</td>
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<tr>
<td>10% w.b. Moisture Content</td>
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<tr>
<td>Rusty Mild Steel</td>
<td>5.5</td>
<td>895</td>
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<tr>
<td>304-2B Stainless Steel</td>
<td>22.0</td>
<td>1085</td>
</tr>
<tr>
<td>Pactene</td>
<td>21.5</td>
<td>1080</td>
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<tr>
<td>15% w.b. Moisture Content</td>
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<tr>
<td>Rusty Mild Steel</td>
<td>5.0</td>
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<tr>
<td>304-2B Stainless Steel</td>
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<td>1520</td>
</tr>
<tr>
<td>Pactene</td>
<td>19.0</td>
<td>1460</td>
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</tbody>
</table>

* Critical Parameters are governed by wall friction considerations and particle interlocking rather than cohesive arching.
Table H.3: Summary of Mass Flow Hopper Geometry Parameters for Huntley ROM Coal, (-2.36mm Test Sample)

<table>
<thead>
<tr>
<th>Wall Material</th>
<th>Instantaneous Conditions</th>
<th>Time Storage Conditions (3Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha_c$</td>
<td>$B_c$</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>(mm.)</td>
</tr>
<tr>
<td>Air Dried Moisture Content</td>
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<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>3.5</td>
<td>120</td>
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<tr>
<td>304-2B Stainless Steel</td>
<td>19.5</td>
<td>140</td>
</tr>
<tr>
<td>Pactene</td>
<td>10.0</td>
<td>130</td>
</tr>
<tr>
<td>6% w.b. Moisture Content</td>
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<td></td>
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<tr>
<td>Rusty Mild Steel</td>
<td>1.5</td>
<td>605</td>
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<tr>
<td>304-2B Stainless Steel</td>
<td>18.0</td>
<td>735</td>
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<tr>
<td>Pactene</td>
<td>22.0</td>
<td>775</td>
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<tr>
<td>10% w.b. Moisture Content</td>
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<tr>
<td>Rusty Mild Steel</td>
<td>4.5</td>
<td>1135</td>
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<tr>
<td>304-2B Stainless Steel</td>
<td>23.5</td>
<td>1395</td>
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<tr>
<td>Pactene</td>
<td>19.0</td>
<td>1330</td>
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<tr>
<td>15% w.b. Moisture Content</td>
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<td>Rusty Mild Steel</td>
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<td>304-2B Stainless Steel</td>
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<td>935</td>
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Table H.4: Summary of Mass Flow Hopper Geometry Parameters for Metropolitan ROM Coal (10% w.b. Moisture Content)

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Table H.5: Summary of Mass Flow Hopper Geometry Parameters for Metropolitan ROM Coal (15% w.b. Moisture Content)

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Table H.6: Summary of Mass Flow Hopper Geometry Parameters for Appin ROM Coal (6% w.b. Moisture Content)

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<td>* * * *</td>
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<td>4.5 705 14.0 365</td>
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<td>18.0 805 27.5 390</td>
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<td>5.5 720 15.0 370</td>
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<tr>
<td>Pactene</td>
<td>20.0 750 30.5 360</td>
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* Critical Parameters are governed by wall friction considerations and particle interlocking rather than cohesive arching.
### Table H.7: Summary of Mass Flow Hopper Geometry Parameters for Appin ROM Coal (10% w.b. Moisture Content)

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Table H.8: Summary of Mass Flow Hopper Geometry Parameters for Appin ROM Coal (15% w.b. Moisture Content)

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<td>1065</td>
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<tr>
<td>Pactene</td>
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<td>1155</td>
</tr>
</tbody>
</table>
Table H.9: Summary of Mass Flow Hopper Geometry Parameters for Westcliff ROM Coal (6% w.b. Moisture Content)

<p>| Wall Material | Instantaneous Conditions | | | TimeStorage Conditions (3Days) | | |
|---------------|--------------------------|----------------|-----------------|--------------------------|
|               | $\alpha_c$ | $B_c$ | $\alpha_p$ | $B_p$ | $\alpha_{ct}$ | $B_{ct}$ | $\alpha_{pt}$ | $B_{ct}$ |
|               | (deg.) | (mm.) | (deg.) | (mm.) | (deg.) | (mm.) | (deg.) | (mm.) |
| Rusty Mild Steel | 2.5 | 52 | 12.0 | 275 | 4.0 | 925 | 14.0 | 480 |
| 304-2B Stainless Steel | * | * | 6.5 | 270 | 7.5 | 960 | 17.0 | 490 |
| Pactene | 18.5 | 615 | 29.0 | 300 | 19.5 | 1085 | 30.5 | 520 |
| <strong>-1.00mm Test Sample</strong> | | | | | | | | |
| Rusty Mild Steel | 1.5 | 530 | 11.0 | 280 | 3.0 | 690 | 12.5 | 360 |
| 304-2B Stainless Steel | 7.5 | 565 | 16.5 | 285 | 12.5 | 765 | 21.5 | 375 |
| Pactene | 22.0 | 660 | 33.5 | 310 | 22.5 | 850 | 34.0 | 300 |
| <strong>-2.36mm Test Sample</strong> | | | | | | | | |
| Rusty Mild Steel | 5.0 | 680 | 14.5 | 350 | 5.5 | 770 | 15.0 | 395 |
| 304-2B Stainless Steel | 16.5 | 770 | 25.5 | 370 | 17.5 | 885 | 27.0 | 420 |
| Pactene | 21.5 | 810 | 32.5 | 380 | 21.5 | 925 | 32.5 | 430 |</p>
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<th>Time Storage Conditions (3 Days)</th>
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<td>(mm.)</td>
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<td>1345</td>
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<tr>
<td>Pactene</td>
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Table H.11: Summary of Mass Flow Hopper Geometry Parameters for Westcliff ROM Coal (15% w.b. Moisture Content)

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<td>Pactene</td>
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<td>1390</td>
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Table H.12: Summary of Mass Flow Hopper Geometry Parameters for Westcliff Product Coal (6% w.b. Moisture Content)

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<td>Pactene</td>
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<td>650</td>
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</table>

| -2.36mm Test Sample    |                                        |                               |                       |                       |                       |                       |                       |                       |
| Rusty Mild Steel       | 2.0                     | 355            | 12.0               | 185         | 5.5                   | 495            | 15.0               | 255         |
| 304-2B Stainless Steel | *                       | *              | 6.5                | 180         | 8.5                   | 515            | 17.5               | 260         |
| Pactene                | 18.5                    | 425            | 28.5               | 200         | 19.5                  | 585            | 30.0               | 275         |

| -4.00mm Test Sample    |                                        |                               |                       |                       |                       |                       |                       |                       |
| Rusty Mild Steel       | 3.5                     | 210            | 13.0               | 110         | 4.0                   | 235            | 13.5               | 120         |
| 304-2B Stainless Steel | *                       | *              | *                  | *           | *                     | *              | *                  | *           |
| Pactene                | 16.5                    | 245            | 26.5               | 120         | 16.5                  | 270            | 27.0               | 130         |

* Critical Parameters are governed by wall friction considerations and particle interlocking rather than cohesive arching.
Table H.13: Summary of Mass Flow Hopper Geometry Parameters for Westcliff Product Coal (10% w.b. Moisture Content)

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-1.00mm. Test Sample

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-2.36mm. Test Sample

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<th>TimeStorage Conditions (3Days)</th>
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Table H.14: Summary of Mass Flow Hopper Geometry Parameters for Westcliff Product Coal (15% w.b. Moisture Content)

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Table H.15: Summary of Mass Flow Hopper Geometry Parameters for Comparison Between Three Different Coals, at similar Particle Distributions and Moisture Contents (-2.36mm Test Sample)

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<td>560</td>
<td>14.0</td>
<td>290</td>
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<td>304-2B Stainless Steel</td>
<td>19.0</td>
<td>695</td>
<td>27.5</td>
<td>310</td>
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<td>18.0</td>
<td>685</td>
<td>28.0</td>
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<td>Westcliff ROM Coal 15% w.b. Moisture Content</td>
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<tr>
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<td>10.0</td>
<td>1135</td>
<td>19.5</td>
<td>565</td>
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<td>1230</td>
<td>27.5</td>
<td>585</td>
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<td>1225</td>
<td>27.5</td>
<td>585</td>
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<td>Queensland ROM Coal 15% w.b. Moisture Content</td>
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<td></td>
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<td>11.0</td>
<td>965</td>
<td>20.5</td>
<td>475</td>
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<td>27.5</td>
<td>1150</td>
<td>38.0</td>
<td>520</td>
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<tr>
<td>Pactene</td>
<td>18.5</td>
<td>1045</td>
<td>28.0</td>
<td>495</td>
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<td>Westcliff Product Coal 15% w.b. Moisture Content</td>
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<td></td>
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<tr>
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<td>12.0</td>
<td>1065</td>
<td>22.5</td>
<td>530</td>
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<tr>
<td>304-2B Stainless Steel</td>
<td>23.5</td>
<td>1175</td>
<td>34.0</td>
<td>560</td>
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<tr>
<td>Pactene</td>
<td>17.5</td>
<td>1115</td>
<td>28.0</td>
<td>545</td>
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Table H.16: Summary of Mass Flow Hopper Geometry Parameters for Westcliff ROM Coal Tumbled and Remixed, (-2.36mm Test Sample).

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<tr>
<td></td>
<td>$\alpha_c$</td>
<td>$B_c$</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>(mm.)</td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>7.0</td>
<td>700</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>21.0</td>
<td>790</td>
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<tr>
<td>Pactene</td>
<td>14.5</td>
<td>745</td>
</tr>
<tr>
<td><strong>15 Control% w.b. Moisture Content</strong></td>
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<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>9.5</td>
<td>730</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>20.5</td>
<td>825</td>
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<tr>
<td>Pactene</td>
<td>16.0</td>
<td>785</td>
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<tr>
<td><strong>10% wb Moisture Content, Tumbled Sample</strong></td>
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<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>5.0</td>
<td>670</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>24.5</td>
<td>800</td>
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<tr>
<td>Pactene</td>
<td>17.0</td>
<td>750</td>
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Table H.17: Summary of Mass Flow Hopper Geometry Parameters for Preliminary Free Ash Test, Westcliff ROM Coal (-4.00mm Test Sample).

<table>
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<th>( \alpha_c ) (deg.)</th>
<th>( B_c ) (mm.)</th>
<th>( \alpha_p ) (deg.)</th>
<th>( B_p ) (mm.)</th>
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<tbody>
<tr>
<td><strong>Control Sample, 11.5 % w.b. Moisture Content</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Rusty Mild Steel</td>
<td>9.5</td>
<td>810</td>
<td>19.5</td>
<td>400</td>
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<td>304-2B Stainless Steel</td>
<td>15.5</td>
<td>880</td>
<td>23.5</td>
<td>405</td>
<td></td>
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<td>Pactene</td>
<td>17.5</td>
<td>900</td>
<td>28.0</td>
<td>415</td>
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<tr>
<td><strong>Coal + Kaolinite, 11.0% w.b. Moisture Content</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>14.5</td>
<td>1270</td>
<td>25.0</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>25.0</td>
<td>1435</td>
<td>35.5</td>
<td>645</td>
<td></td>
</tr>
<tr>
<td>Pactene</td>
<td>19.0</td>
<td>1340</td>
<td>30.0</td>
<td>625</td>
<td></td>
</tr>
<tr>
<td><strong>Coal + Bentonite Sample, 11.4% w.b. Moisture Content</strong></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>16.5</td>
<td>1105</td>
<td>27.0</td>
<td>510</td>
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</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>26.0</td>
<td>1265</td>
<td>37.0</td>
<td>535</td>
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<td>Pactene</td>
<td>20.0</td>
<td>1160</td>
<td>30.5</td>
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Table H.18: Summary of Mass Flow Hopper Geometry Parameters for Westcliff ROM Coal + Kaolin, (-4.00mm Test Sample).

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<th>Instantaneous Conditions</th>
<th>Time/Storage Conditions (3Days)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha_c$ (deg.)</td>
<td>$B_c$ (mm.)</td>
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<tr>
<td><strong>5.3% w.b. Moisture Content</strong></td>
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<td></td>
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<tr>
<td>Rusty Mild Steel</td>
<td>8.5</td>
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</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>17.5</td>
<td>525</td>
</tr>
<tr>
<td>Pactene</td>
<td>20.0</td>
<td>540</td>
</tr>
<tr>
<td><strong>10.3% w.b. Moisture Content</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>13.5</td>
<td>720</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>22.0</td>
<td>825</td>
</tr>
<tr>
<td>Pactene</td>
<td>18.5</td>
<td>780</td>
</tr>
<tr>
<td><strong>12.2% w.b. Moisture Content</strong></td>
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<td></td>
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<td>Rusty Mild Steel</td>
<td>16.5</td>
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Table H.19: Summary of Mass Flow Hopper Geometry Parameters for Westcliff ROM Coal + Bentonite, (-4.00mm Test Sample).

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<th>TimeStorage Conditions (3Days)</th>
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<tr>
<td></td>
<td>$\alpha_c$</td>
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<tr>
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<td>(mm.)</td>
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<tr>
<td>Rusty Mild Steel</td>
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<td>290</td>
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<td>Pactene</td>
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<td></td>
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<tr>
<td>Rusty Mild Steel</td>
<td>15.0</td>
<td>620</td>
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<tr>
<td>304-2B Stainless Steel</td>
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<tr>
<td>Pactene</td>
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<td>640</td>
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<td><strong>10.0% w.b. Moisture Content</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>12.0</td>
<td>710</td>
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<td>304-2B Stainless Steel</td>
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<td>Pactene</td>
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Table H.20: Summary of Mass Flow Hopper Geometry Parameters for Westcliff ROM Coal Control and Coal + Fines Samples for Coal + Free Clay Program, (-4.00mm Test Sample).

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<th>TimeStorage Conditions (3Days)</th>
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<td>$\alpha_c$</td>
<td>$B_c$</td>
</tr>
<tr>
<td></td>
<td>(deg.)</td>
<td>(mm.)</td>
</tr>
<tr>
<td>Control Sample, 10.0% w.b. Moisture Content</td>
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<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>304-2B Stainless Steel</td>
<td>7.5</td>
<td>495</td>
</tr>
<tr>
<td>Pactene</td>
<td>12.0</td>
<td>530</td>
</tr>
<tr>
<td>Control Sample, 15.0% w.b. Moisture Content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rusty Mild Steel</td>
<td>13.0</td>
<td>1115</td>
</tr>
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<td>24.5</td>
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<td>Pactene</td>
<td>19.0</td>
<td>1190</td>
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<tr>
<td>Coal + Fines Sample, 5.0% w.b. Moisture Content</td>
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<tr>
<td>Rusty Mild Steel</td>
<td>6.0</td>
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<td>1520</td>
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<td>1375</td>
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<td>23.0</td>
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APPENDIX I

COMPUTER PROGRAM FP, FLOW PROPERTY PROCESSING AND ANALYSIS

Table I.1 FORTRAN Subroutines of Program FP

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<td>COMPRM.FOR</td>
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<td>DRAW.FOR</td>
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<td>RBH.FOR</td>
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I.1 PROGRAM LISTING OF FPMAIN.FOR

PROGRAM FPMAIN
C A FORTRAN GRAPHICS PROGRAM TO READ AND PROCESS EXPERIMENTAL FLOW
C PROPERTY DATA. THE FLOW PROPERTIES ARE PRESENTED GRAPHICALLY
C AND ALSO DESCRIBED BY VARIOUS CHARACTERISTIC EQUATIONS. THE
C FOLLOWING FLOW PROPERTIES MAY BE PROCESSED :-
C (I) INSTANTANEOUS YIELD LOCUS, BOTH LOW AND HIGH PRESSURE.
C (II) TIME YIELD LOCUS, BOTH LOW AND HIGH PRESSURE.
C (III) PLOT AND EQUATION FIT BOTH THE LOW AND HIGH
C PRESSURE INSTANTANEOUS AND TIME FLOW FUNCTIONS.
C PROVIDE ALSO DELTA AND PHI-T VARIATIONS.
C (IV) PLOT AND CURVE FIT WALL YIELD DATA
C (V) PRESENT THE VARIATION OF PHI-W FOR VARIOUS WALL YIELD LOCI
C KNOWING THE DELTA VARIATION. PROVIDE BOTH GRAPHICAL AND
C CURVE FITTED EQUATION FIT.

COMMON /VALUES/FPVAL(10,5)
COMMON /B/TITLEB,/C/TITLEC,/T/XTIME
COMMON /HPOUT/ PFILE,PLNUM
INTEGER GETOPT,OPTX
CHARACTER*30 FILE1
CHARACTER*12 PFILE
CHARACTER*(30) XTIME
CHARACTER*(60) TITLEB, TITLEC
CHARACTER*3 PLNUM
CHARACTER*77 LINE
CHARACTER*11 CTIME1, CTIME2
CHARACTER*8 CDATE, FNAME
C Record keeping
C
CALL DATE( CDATE )
CALL TIME( CTIME1 )
C CALL UNDERO(.TRUE.)
CALL OVEFL(.TRUE.)
PLNUM='--00'
TITLEB='MATERIAL:
TESTED:'
WRITE OUT TITLE - WHICH HAS BEEN STORED IN FILE D:FP-TITLE

OPEN(28,FILE='D:FP-TITLE')
CALL MONCLEAR(0)
PRINT,'1m1;1f'
PRINT,CHAR(201),(CHAR(205),111=2,78),CHAR(187)
DO 7 I=2,23
READ(28,'(1X,A77)',END=39) LINE
PRINT,CHAR(186),LINE,CHAR(186)
7 PRINT,CHAR(200),(CHAR(205),111=2,78),CHAR(188)
CLOSE(28)
PRINT,'1m25;18f Press H for help or any key to continue'
OPEN(27,FILE='CON',ACCESS='TRANSPARENT')
IDUM=GETOPT()
C IF HELP HAS BEEN REQUESTED WRITE OUT THE FILE D:FP-HELP A PAGE AT A TIME

IF( IDUM.EQ.INCHAR('h') .OR. IDUM.EQ.INCHAR('H') ) THEN
CALL MONCLEAR(0)
CALL SYSTEM("DIR \FP\HELP > D:HELP.TMP")
OPEN(28,FILE='D:HELP.TMP')
OPEN(26,FILE='D:FP-HELP',ACCESS='DIRECT',RECF8,FORM='FORMATTED'
')
READ(28,'(A)') (LINE,11=1,6)
PRINT,CHAR(201),(CHAR(205),111=2,78),CHAR(187)
DO 48 II=2,22
48 PRINT,CHAR(186),(' ',II=1,77),CHAR(186)
PRINT,CHAR(200),(' ',II=1,77),CHAR(188)
PRINT,'25;9f7m0m Exit ?mNam  Next page 7mB0
NRCD=0
40 READ(28,'(A)',END=41) FNAME(1:8)
IF( FNAME(1:1).NE.' ') THEN
NRCD=NRCD+1
WRITE(26,'(A8)',REC=NRCD) FNAME(1:8)
GOTO 40
41 IF(I.CLE.10) THEN
CLOSE( 28 )
READ(26,'(A8)',REC=IRCD) FNAME(1:8)
OPEN(28,FILE='\FP\HELP'//FNAME(1:8))
8 DO 9 I=2,23
READ(28,'(A77)',END=38) LINE
IF( I.LT.10 ) THEN
PRINT '(1X,’’,I1,’’;2f’’,A,’’,I1,’’;2f’’)', I,
* LINE,1-1
ELSE IF( I.EQ.10 ) THEN
PRINT '(1X,’’,I2,’’;2f’’,A,’’,I1,’’;2f’’)', I,
* LINE,1-1
ELSE
PRINT '(1X,’’,I2,’’;2f’’,A,’’,I2,’’;2f’’)', I,
* LINE,1-1
ENDIF
CONTINUE

IF ( I.LT.23 ) THEN
   DO 49 III=I,22
      PRINT, CHAR(186),('  ',III=1,77),CHAR(186)
   ENDIF
   PRINT,'24;2f'
   CLOSE( 28 )
   IDUM=GETOPT()
   IF( IDUM.EQ.ICHAR('N') .OR. IDUM.BQ.ICHAR('n') ) THEN
      IRCD=IRCD+1
      IF( IRCD.GT.NRCD ) IRCD=1
      GOTO 42
   ELSEIF( IDUM.EQ.ICHAR('B') .OR. IDUM.EQ.ICHAR('b') ) THEN
      IRCD=IRCD-1
      IF( IRCD.LT.l ) IRCD=NRCD
      GOTO 42
   ELSEIF( IDUM.BQ.ICHAR('P') .OR. IDUM.BQ.ICHAR('p') ) THEN
      CALL SYSTEM('PRINT \FP\HELP"\FNAME(1:8)" > NUL")
      GOTO 42
   ENDIF
   CLOSE(26)
ENDIF

C
C OPEN PLOT PACKAGE
C
CALL PPBGN(' ')
NYL=0
NHYL=0
C
C CLEAR THE SCREEN AND SHOW BULK SOLIDS CHARACTERISTICS INPUT PAGE
C
CALL NONCLEAR(O)
PRINT,'llti'
PRINT,'l;lf'
WRITE(6,100)
100 FORMAT(27X,'BULK SOLID CHARACTERISTICS')
PRINT, (CHAR(205),III=1,80),'4;lf*
WRITE(6,110)
110 FORMAT(' ENTER MATERIAL DATA AS REQUESTED')
C
C OPEN FILES REQUIRED AND READ MATERIAL PROPERTIES
C
PRINT,'Om'
WRITE(6,120)
120 FORMAT(/,' MATERIAL TESTED: 4m
   *Om',/)
WRITE(6,130)
130 FORMAT(/,' MOISTURE CONTENT: 4m Om',
   */)
WRITE(6,140)
140 FORMAT(/,' DATE TESTED: 4m Om',/)
WRITE(6,150)
150 FORMAT(/,' TEMPERATURE <AMBIENT>: 4m Om')
PRINT,'8;24f'
READ(5, '(A)')TITLEB(11:39)
PRINT,'12;24f'
READ(5, '(A)')TITLEB(19:39)
PRINT,'16;24f'
READ(5, '(A)')TITLEB(49:60)
PRINT,'20:24f'
READ(5,'(A)')TITLEC(54:60)
IF(TITLEC(54:54).EQ. ') TITLEC(54:60)='AMBIENT'

C PRESENT FILE ASSIGNMENT PAGE

CALL MONCLEAR(0)
PRINT,'1m1;1f'
WRITE(*,102)
102 FORMAT(29X,'REPORT FILE ASSIGNMENT')
PRINT,(CHAR(205),III=1,80)
PRINT,'6;4fOmPROCESSED DATA STORAGE FILE <lmREPORT0m>: '
PRINT,'6;42f4m Omc6;42f'
READ(*,'(A)') FILE11
IF( LEN(CHARNB(FILE11)).EQ.1 ) FILE11='REPORT'
OPEN(11,FILE=FILE11)
PRINT,'8;7fPLOT STORAGE FILES CODE NAME <lmFPOm>: '
PRINT,'8;42f4m Omc8;42f'
READ(*,'(A)') FFILE
IF( LEN(CHARNB(FFILE)).EQ.1 ) FFILE='FP'
OPEN(12,FILE='DATA')

C WRITE OUT MATERIAL DETAILS TO FILES 11
C
WRITE(11,'(A,/)') TrTLC(l:39)
WRITE(11,'(A,/)') TrTLC(l:40)
WRITE(11,'(A,/)') TITLEB(41:60)
WRITE(11,160)
160 FORMAT(' MATERIAL PARAMETER EQUATIONS ARE IN STRESS UNITS OF ',
',*/,' KILOPASCALS. ',/)

C WHICH PLOT IS REQUIRED
C
10 CALL MONCLEAR(0)
PRINT,'1m'
PRINT,'1;1f'
WRITE(*,169)
169 FORMAT(25X,'FLOW PROPERTY TESTS AVAILABLE',26(' '))
PRINT,(CHAR(205),III=1,80), '4;If'
WRITE(6,170)
170 FORMAT(/,' WHICH FLOW PROPERTY TEST DO YOU REQUIRE TO PROCESS')
PRINT, 'On'
PRINT,'7;1f'
WRITE(*,175)
175 FORMAT(' ESC - FINISH',
',*/,' F1 - INSTANTANEOUS YIELD LOCI AND FLOW FUNCTION',
',*/,' F2 - TIME YIELD LOCI AND FLOW FUNCTIONS',
',*/,' F3 - WALL YIELD LOCI',
',*/,' F4 - KINEMATIC ANGLE OF WALL FRICTION VARIATION',
',*/,' F5 - BULK DENSITY VARIATION')
PRINT,'1m'
WRITE(*,176)
176 FORMAT(/,' OPTION ')
IF(OPTION.EQ.1) THEN
CALL IYL(NYL,NHYL,1)
C
WRITE OUT TO FILE 12
C
WRITE(12, '(/''INST'')')
DO 20 I=1,NYL
WRITE(12,'(3F8.2)') FPVAL(I,1),FPVAL(I,2),FPVAL(I,3)
20 CONTINUE
IF(NHL,NE.0) THEN
DO 30 I=NYL, NyL+NHL
WRITE(12,'(3F8.2)') FPVAL(I,1),FPVAL(I,2),FPVAL(I,3)
30 CONTINUE
ENDIF
C
PROCESS TIME YIELD LOCAND FLOW FUNCTIONS
C
ELSE IF(OPTION.EQ.2) THEN
C
READ INSTANTANEOUS DATA IF NECESSARY
C
IF(NYL.LE.0) THEN
CALL MGNCLEAR(4)
WRITE(6,210)
210 FORMAT(/,' PLEASE ENTER INSTANTANEOUS YIELD DATA FIRST',
* '/,' PRESS RETURN TO ENTER INSTANTANEOUS DATA OR F1 TO',
* ' RETURN TO MAIN MENU')
IGO=GETOPT()
IF( IGO.EQ.0 )THEN
CALL IYL(NYL,NHYL,1)
ELSE
GOTO 10
ENDIF
ENDIF
CALL TYL(NYL,NHYL,1)
C
ELSE IF(OPTION.EQ.3) THEN
C
PROCESS WALL YIELD LOCI
C
CALL WYL
C
ELSE IF(OPTION.EQ.4) THEN
C
DISPLAY KINEMATIC ANGLE OF WALL FRICTION VARIATION
C
CALL PHIGPH(0)
C
ELSE IF(OPTION.EQ.5) THEN
C
PROCESS BULK DENSITY
C
CALL CMPRM
C
ENDIF
C
RETURN TO TOP OF PROGRAM FOR NEXT OPTION IF REQUIRED
C
IF(OPTION.NE.0) GO TO 10

WRITE OUT CONCLUDING REMARKS

CALL M3NCLEAR(0)

NN=LEN(CHARNB(PFILE))

IF( NN.GT.5 ) NN=5

IF( PLANUM.EQ. '"-00' ') THEN
   PRINT,' NO PLOT FILES PRODUCED'
ELSEIF( PLANUM.EQ. '"-01' ') THEN
   PRINT,' YOUR PLOT FILE IS ',PFILE(1:NN)/"-01'/'.PLT'
ELSE
   PRINT,' YOUR PLOTS EXIST IN FILES NAMED: ',PFILE(1:NN),"-01.PLT'

ENDIF

WRITE(6,240) FILE11

240 FORMAT(/,' A REPORT LISTING DATA POINTS',
      '* AND FITTED EQUATIONS',
      '* EXIST IN FILE :',A)

WRITE(6,260)

260 FORMAT(/,' THE ABOVE FILE MAY BE DISPLAYED:',
      '* 1: to print (if a printer is attached) PRINT filename',/
      '* 2: to display on terminal TYPE filename MORE')

CLOSE FILES USED

CLOSE(11)
CLOSE(12)

TERMINATE PLOT PACKAGE

CALL PPEND

Record keeping - elapsed time

READ(CTIME1,'(3(I2,1X))') IHR,IMIN,ISEC
CALL TIME( CTIME2 )
READ(CTIME2,'(3(I2,1X))') JHR,JMIN,JSEC

KSEC=JSEC-ISEC

IF( KSEC.LT.0 ) THEN
   JMIN=JMIN+1
   KSEC=60+KSEC
ENDIF

KMIN=JMIN-IMIN

IF( KMIN.LT.0 ) THEN
   JHR=JHR+1
   KMIN=60+KMIN
ENDIF

KHR=JHR-IHR

IF( KHR.LT.0 ) KHR=KHR+24

OPEN(30,FILE='\BAM\FP-STAT.SYS',ACCESS='APPEND')
BACKSPACE 30
READ(30,'(A)') END=1 LINE
READ(LINE, '(24X,I5)') NREC
NREC=NREC+1
GOTO 2

1 NREC=1

2 BACKSPACE 30
WRITE(30,'(A7,A8,A7,A11,A12,2(I2,A1),I2)') ' DATE: ',CDATE,' TIME:
I.2 FLOW PROPERTY REPORT PRODUCED BY PROGRAM FP FOR EXAMPLE

MATERIAL: RUN OF MINE COAL

MOISTURE CONTENT: 10% Nom.

TESTED: JANUARY, 1988

TEMPERATURE: AMBIENT

MATERIAL PARAMETER EQUATIONS ARE IN STRESS UNITS OF KILOPASCALS.

INSTANTANEOUS YIELD LOCI DATA

DATA FOR YIELD LOCUS: 1
END POINT OF YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
4.882 5.013

POINTS ON YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
3.014 3.923
2.391 3.425
2.080 3.176
1.769 2.927
DATA FOR YIELD LOCUS: 2
END POINT OF YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
3.637 3.855
POINTS ON YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
2.385 3.151
2.074 2.933
1.762 2.696
1.451 2.385

DATA FOR YIELD LOCUS: 3
END POINT OF YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
2.379 2.553
POINTS ON YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
1.445 2.117
1.289 1.931
1.133 1.818
0.978 1.719

TIME YIELD LOCUS DATA
CONSOLIDATION TIME: 3 Days

DATA FOR TIME YIELD LOCUS: 1
POINTS ON TIME YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
3.014 4.372
2.391 3.715
2.080 3.543
1.769 3.164

DATA FOR TIME YIELD LOCUS: 2
POINTS ON TIME YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
2.696 3.674
2.385 3.375
2.074 3.156
1.762 2.860

DATA FOR TIME YIELD LOCUS: 3
POINTS ON TIME YIELD LOCUS
SIGMA - kPa SIGMAC - kPa
1.445 2.242
1.289 2.130
1.133 1.974
0.978 1.850

FLOW FUNCTION DATA

<table>
<thead>
<tr>
<th>SIGMA - kPa</th>
<th>SIGMAC - kPa</th>
<th>DELTA - Deg</th>
<th>SIGMA CT - kPa</th>
<th>PHI t - Deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.880</td>
<td>6.292</td>
<td>53.51</td>
<td>7.056</td>
<td>43.47</td>
</tr>
<tr>
<td>8.994</td>
<td>5.175</td>
<td>55.57</td>
<td>5.904</td>
<td>40.53</td>
</tr>
<tr>
<td>5.707</td>
<td>3.772</td>
<td>59.64</td>
<td>4.397</td>
<td>40.56</td>
</tr>
</tbody>
</table>
INSTANTANEOUS FLOW FUNCTION \[ F = 0.41 \sigma_1 + 1.46 \]

EFFECTIVE ANGLE OF INTERNAL FRICTION \[ \Delta = 1.52 - \frac{3358.91}{(52.71 + \sigma_1)} \]

TIME FLOW FUNCTION \[ F_T = 0.43 \sigma_1 + 1.96 \]

STATIC ANGLE OF INTERNAL FRICTION \[ \phi_T = 0.46 \sigma_1 + 37.44 \]

COMPRESSIBILITY DATA

NEET MASS = 32.33 GRAMS

<table>
<thead>
<tr>
<th>V Kg</th>
<th>H mm</th>
<th>SIGMA kPa</th>
<th>RHO Kg/m**3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>15.82</td>
<td>0.37</td>
<td>645.13</td>
</tr>
<tr>
<td>0.62</td>
<td>14.40</td>
<td>1.92</td>
<td>708.85</td>
</tr>
<tr>
<td>1.12</td>
<td>13.69</td>
<td>3.46</td>
<td>745.67</td>
</tr>
<tr>
<td>2.12</td>
<td>13.13</td>
<td>6.55</td>
<td>777.40</td>
</tr>
<tr>
<td>4.12</td>
<td>12.47</td>
<td>12.73</td>
<td>818.57</td>
</tr>
<tr>
<td>8.12</td>
<td>11.89</td>
<td>25.09</td>
<td>858.79</td>
</tr>
<tr>
<td>16.12</td>
<td>11.33</td>
<td>49.81</td>
<td>901.16</td>
</tr>
</tbody>
</table>

\[ \rho = 775.01 \left( \frac{\sigma_1}{5.925} \right)^{0.0694} \]

WALL YIELD LOCI DATA

DATA FOR WALL YIELD LOCUS: 1
WALL MATERIAL: RUSTY MILD STEEL

<table>
<thead>
<tr>
<th>SIGMA - kPa</th>
<th>TAU - kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.504</td>
<td>0.374</td>
</tr>
<tr>
<td>1.750</td>
<td>1.245</td>
</tr>
<tr>
<td>2.995</td>
<td>2.117</td>
</tr>
<tr>
<td>4.241</td>
<td>2.865</td>
</tr>
<tr>
<td>5.486</td>
<td>3.425</td>
</tr>
<tr>
<td>6.732</td>
<td>4.347</td>
</tr>
<tr>
<td>7.977</td>
<td>4.957</td>
</tr>
<tr>
<td>9.223</td>
<td>5.437</td>
</tr>
<tr>
<td>10.468</td>
<td>6.277</td>
</tr>
<tr>
<td>11.714</td>
<td>6.850</td>
</tr>
</tbody>
</table>

\[ S = 0.57 \sigma + 0.30 \]

DATA FOR WALL YIELD LOCUS: 2
WALL MATERIAL: PACTENE

<table>
<thead>
<tr>
<th>SIGMA - kPa</th>
<th>TAU - kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.504</td>
<td>0.336</td>
</tr>
<tr>
<td>1.750</td>
<td>0.803</td>
</tr>
<tr>
<td>2.995</td>
<td>1.245</td>
</tr>
<tr>
<td>4.241</td>
<td>1.644</td>
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<tr>
<td>5.486</td>
<td>2.105</td>
</tr>
<tr>
<td>6.732</td>
<td>2.510</td>
</tr>
<tr>
<td>7.977</td>
<td>2.896</td>
</tr>
<tr>
<td>9.223</td>
<td>3.413</td>
</tr>
<tr>
<td>10.468</td>
<td>3.880</td>
</tr>
<tr>
<td>11.714</td>
<td>4.353</td>
</tr>
</tbody>
</table>

\[ S = 0.35 \sigma + 0.16 \]
DATA FOR WALL YIELD LOCUS: 3  
WALL MATERIAL: 304-2B STAINLESS STEEL  

<table>
<thead>
<tr>
<th>SIGMA - kPa</th>
<th>TAU - kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.504</td>
<td>0.448</td>
</tr>
<tr>
<td>1.750</td>
<td>0.841</td>
</tr>
<tr>
<td>2.995</td>
<td>1.208</td>
</tr>
<tr>
<td>4.241</td>
<td>1.588</td>
</tr>
<tr>
<td>5.486</td>
<td>1.943</td>
</tr>
<tr>
<td>6.732</td>
<td>2.292</td>
</tr>
<tr>
<td>7.977</td>
<td>2.616</td>
</tr>
<tr>
<td>9.223</td>
<td>2.989</td>
</tr>
<tr>
<td>10.468</td>
<td>3.338</td>
</tr>
<tr>
<td>11.714</td>
<td>3.624</td>
</tr>
</tbody>
</table>

\[ S = 0.28 \times \text{SIGMA} + 0.35 \]

END OF REPORT.
# APPENDIX J

**COMPUTER PROGRAM BD, DETERMINATION OF MASS FLOW HOPPER GEOMETRY PARAMETERS**

Table J.1  **FORTRAN Subroutines of Program BD**

<table>
<thead>
<tr>
<th>SUBROUTINE</th>
<th>SIZE(bytes)</th>
<th>NUMBER OF LINES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALFA.FOR</td>
<td>655</td>
<td>24</td>
</tr>
<tr>
<td>ALVSB.FOR</td>
<td>1479</td>
<td>59</td>
</tr>
<tr>
<td>BDDRIVER.FOR</td>
<td>3005</td>
<td>123</td>
</tr>
<tr>
<td>BDMAIN.FOR</td>
<td>4082</td>
<td>136</td>
</tr>
<tr>
<td>CRITB.FOR</td>
<td>3744</td>
<td>138</td>
</tr>
<tr>
<td>DERIV1.FOR</td>
<td>763</td>
<td>27</td>
</tr>
<tr>
<td>FALPHA.FOR</td>
<td>283</td>
<td>13</td>
</tr>
<tr>
<td>FLFAC.FOR</td>
<td>807</td>
<td>33</td>
</tr>
<tr>
<td>GAMMA.FOR</td>
<td>221</td>
<td>12</td>
</tr>
<tr>
<td>GETOPT.FOR</td>
<td>423</td>
<td>17</td>
</tr>
<tr>
<td>HPSERVER.FOR</td>
<td>4078</td>
<td>159</td>
</tr>
<tr>
<td>INPUT.FOR</td>
<td>10888</td>
<td>344</td>
</tr>
<tr>
<td>MASSFLOW.FOR</td>
<td>9925</td>
<td>312</td>
</tr>
<tr>
<td>MAXLAB.FOR</td>
<td>366</td>
<td>16</td>
</tr>
<tr>
<td>MINVI.FOR</td>
<td>5726</td>
<td>192</td>
</tr>
<tr>
<td>MONCLEAR.FOR</td>
<td>615</td>
<td>24</td>
</tr>
<tr>
<td>PHIFIN.FOR</td>
<td>2526</td>
<td>84</td>
</tr>
<tr>
<td>PLOT.FOR</td>
<td>2123</td>
<td>69</td>
</tr>
<tr>
<td>READ.FOR</td>
<td>512</td>
<td>23</td>
</tr>
<tr>
<td>SALPHA.FOR</td>
<td>3269</td>
<td>123</td>
</tr>
<tr>
<td>SCALE.FOR</td>
<td>1821</td>
<td>79</td>
</tr>
<tr>
<td>TEXT1.FOR</td>
<td>1174</td>
<td>42</td>
</tr>
<tr>
<td>VXCLEAR.FOR</td>
<td>152</td>
<td>9</td>
</tr>
<tr>
<td>VXSERVER.FOR</td>
<td>3978</td>
<td>160</td>
</tr>
</tbody>
</table>
PROGRAM BDMAIN
C THE MAIN ACCESS PROGRAM FOR MASS FLOW
C HOPPER GEOMETRY PARAMETER DETERMINATION.
C AFTER ENTERING THE DATA FILENAMES, THE FLOW PROPERTIES OF
C BULK SOLID ARE ENTERED AS EMPIRICAL EQUATIONS.
C
COMMON /DATA/ M,DEL(3),AREC,GAM(3),FF(2,2),FFI
COMMON /RADIUS/ RTOD,DTOR,PYE
COMMON /TEXT/ SOLNAM,BLINE,DLINE
COMMON /MAT/ NNM,WBL,WYNAM(10),WYL(10,3)
COMMON /HPOUT/ PFILE,PLNUM

CHARACTER*60 SOLNAM
CHARACTER*77 LINE
CHARACTER*80 DLINE,BLINE
CHARACTER*25 FILE11,PFILE
CHARACTER*3 PLNUM
CHARACTER*11 WMNAM
INTEGER GEHOPT

RTOD=0.5729578E+2
DTOR=0.17453292E-1
PYE=3.1415926

DO 13 1=1,80
   BLINE(I:I)='  '
   DUNE(I:I)=CHAR(205)

PLNUM='000'

CREATE PLOT FILE

CALL PPBGN ('BIN DIMENSIONS')
OPEN(27,FILE='CON',ACCESS='TRANSPARENT')

SET UP UNDER AND OVER FLOW ERRORS FOR MATH PACK

CALL UNDFL(.TRUE.)
CALL OVEFL(.TRUE.)

CALL MONCLEAR(0,0)
CALL VCLEAR

Write out title - which has been stored in file ['\BD\BD-TITLE.TXT']

OPEN(28,FILE='\BD\BD-TITLE.TXT')
PRINT,'1ml:If'
PRINT,CHAR (201), (CHAR (205),III=2,78),CHAR (187)
   DO 7 I=2,23
      READ(28,'(1X,A?7)',END=39) LINE
      PRINT,CHAR (186),LINE,CHAR (186)
   7  PRINT,CHAR (200), (CHAR (205),III=2,78),CHAR (188)
CLOSE(28)
PRINT,'0m25;18f Press H for help or any key to continue '
C IF HELP HAS BEEN REQUESTED WRITE OUT THE FILE \BD\BD-HELP.TXT A
C PAGE AT A TIME
C
C IDUM=GETOPT()
IF( IDUM.EQ.ICHAR('h') .OR. IDUM.EQ.ICHAR('H') ) THEN
   CALL MONCLEAR(0,0)
   OPEN(28,FILE='\BD\BD-HELP.TXT')
   PRINT,CHAR(201),(CHAR(205),111=2,78),CHAR(18?)
   DO 9 I=2,23
      READ(28,'(1X,A77)',END=38) LINE
   9 PRINT,CHAR(186),LINE,CHAR(86)
   PRINT,CHAR(200),(CHAR(205),111=2,78),CHAR(188)
   PRINT25;16fPress E to exit or any key for the next page'
   IDUM=GETOPT()
   IF( IDUM.NE.ICHAR('e') ) THEN
      PRINT,'2;1f'
      GOTO 8
   ENDIF
38 IF( I.LT.23 ) THEN
   LINE=' '
   WRITE(6,'(1X,A77,/)') (LINE,111=1,22)
   ENDIF
   PRINT,CHAR(200),(CHAR(205),111=2,78),CHAR(188)
   PRINT,'25;18fPress any key to return to the program'
   IDUM=GETOPT()
   CLOSE(28)
   END IF
   CALL MONCLEAR(0,0)
C FIRST PAGE OF DATA ENTRY
C PRINT, '2;26fBULK SOLID FLOW CHARACTERISTICS'
C PRINT, 'DLINE'
C PRINT, 'Om'
C PRINT, '10;1fINPUT EQUATION SUMMARY FILE <mEQN-SUMm>: '
C PRINT, '10;41f0m10;41f'
C READ(*,'(A)') FILE11
C IF (LEN(CHARNB(FILE11)).EQ.1) FILE11='EQN-SUM'
C OPEN(11,FILE=FILE11)
C PRINT, '12;6fPLOT STORAGE FILES CODE NAME <mBD-Plom>: '
C PRINT, '12;41f0m12;41f'
C READ(*,'(A)') FILE
C IF (LEN(CHARNB(FILE)).EQ.1 ) FILE='BD'
C PRINT, '12;1f PLOT DATA STORAGE FILE <mBD-PLoToom>: '
C PRINT, '12;41f0m'
C PRINT, '12;41f'
C CALL MONCLEAR(10,12)
C Call the subroutine for the data equation input
C required by the program
C
10 CALL INPUT
C CALL MONCLEAR(0,0)
C
20 PRINT, '1m2;29fHOPPER GEOMETRY DESIGN',DLINE, 'Om'
C PRINT, '5;2fSELECT FROM THE FOLLOWING'
C PRINT, '7;2fESC - FINISH'
C PRINT, '8;2ff1 - CALCULATE MASS FLOW HOPPER GEOMETRY'
C PRINT, '9;2ff2 - ALTER BULK SOLID FLOW PROPERTIES'
71 PRINT, '11;24f1mOPTION -Om'
J.2 DATA INPUT SUMMARY PRODUCED BY PROGRAM BD FOR EXAMPLE

BIN DESIGN PROGRAM INPUT.

MATERIAL TESTED: RUN OF MINE COAL, 10% Nom.

FLOW FUNCTION: \( \Sigma_{MC} = 0.41\Sigma_1 + 1.46 \)

FLOW FUNCTION: \( \Sigma_{MC} = 0.43\Sigma_1 + 1.96 \)

EFFECTIVE ANGLE OF FRICTION: \( \Delta = 1.52 - \frac{3358.91}{(52.71 + \Sigma_1)} \)

BULK DENSITY VARIATION: \( \rho = 775.01(\Sigma_1/5.925)^{0.0694} \)

WALL YIELD LOCUS EQUATION FOR RUSTY MS
\( \tau = 0.57\Sigma_1 + 0.30 \)

WALL YIELD LOCUS EQUATION FOR PACTENE
\( \tau = 0.35\Sigma_1 + 0.16 \)

WALL YIELD LOCUS EQUATION FOR 304-2B SS
\( \tau = 0.28\Sigma_1 + 0.35 \)
APPENDIX K

PUBLICATIONS WHILE Ph.D CANDIDATE

Refereed Articles.

1. Arnold, P.C., McLean, A.G. and Moore, B.A.
   'The Application of Computer Graphics to the Flow Property Testing

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APPENDIX L

REPRINTS OF SELECTED RELEVANT PAPERS

i) Moore, B.A. and Arnold, P.C. and McLean, A.G.

ii) Moore, B.A. and Arnold, P.C.

iii) Moore, B.A. and Arnold, P.C.

iv) Moore, B.A. and Arnold, P.C.

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