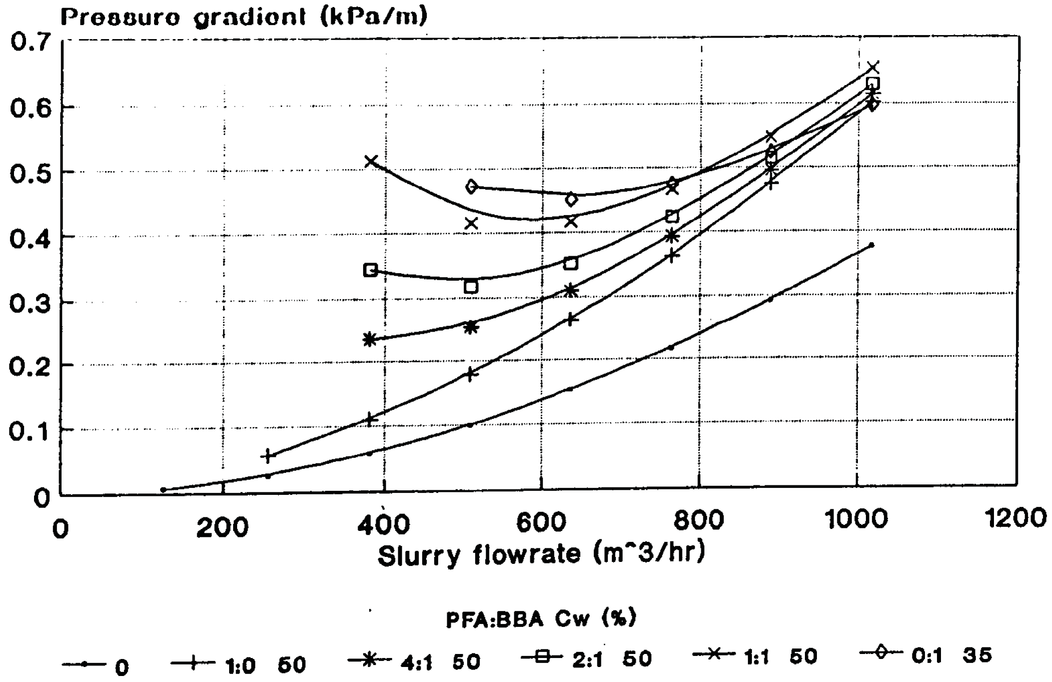


Figure 9.46 PFA:BBA mixture pressure gradients response for slurry concentrations of the order of 50%

4) The slurries tested were all pumped with centrifugal pumps. A practical limitation imposed for the use of the centrifugal pumps for the transport of medium phase slurries is the friction gradient of the slurry transported and the change in the pump performance characteristic as a result of the presence of the solids in the pump. A typical indication of the derating of a centrifugal pump transporting a non Newtonian slurry is illustrated in the following diagram(128).

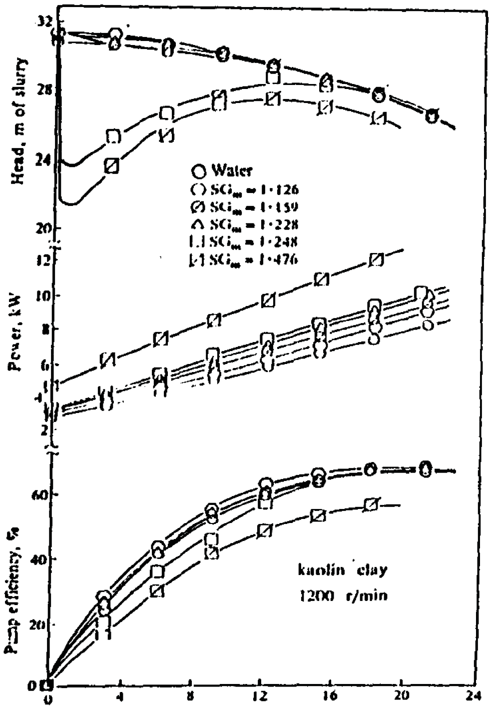


Figure 9.47 The influence of fine solids on the performance characteristic of a centrifugal pump(127).

This observation is global and is dependent on the distance that the slurry is to be transported, the static head and the maximum head possible from a series of centrifugal pumps.

5) The slurries tested were all subjected to shutdown and restart tests. All the slurries tested were restarted with the original slurry deposited in the pipeline. In all cases provided a smaller layer of water existed on top of the deposited layer, the slurries were easily restarted. This restart characteristic is thus influenced by the maximum packing density of the slurry transported. The actual resuspension of the deposited layer is dependent on the particle size, the height of the deposited layer and the presence of any pozzuolonic characteristics.

The PFA slurry was resuspended by reverse dune erosion (Fig. 9.48) while the larger, non pozzuolonic slurries were resuspended in a layered fashion.

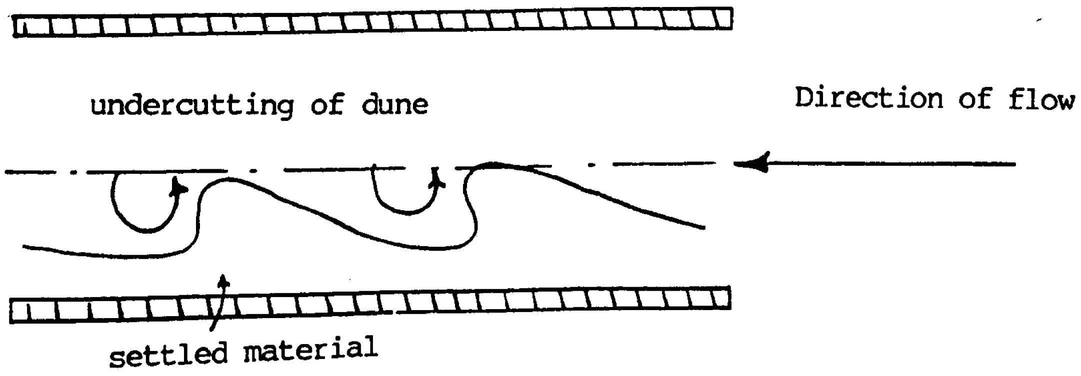


Figure 9.48 Reverse dune erosion and resuspension of the PFA slurries

6) The maximum transport concentration is influenced by the maximum packing density. In general for the slurries tested, the larger the average particle size the larger the maximum packing density. Where insufficient fines are present, the transition from the turbulent medium concentration slurry will manifest itself in a full cross-section bed flow as proposed by Streat and Wilson(39,41). Practical experience of the slurries tested indicates that transportation in this form is prone to blockages and restart difficulties and thus limited to very short distances (Chapter 8).

Where sufficient fines are present, the transitions from a turbulent flow settling slurry will result in a pseudohomogeneous paste, that can be restarted and pumped albeit at high pressure gradients (Chapter 8).

7) The medium phase slurries are characterised by non-Newtonian rheology. This is especially the case for fine particle slurries. This reverts to Newtonian rheology, the lower the concentration and the coarser the particle size. The average particle size only gives an indication and the quantity of sub 30 micron present will also influence results.

Prediction procedures for estimating the friction gradients should thus incorporate the non-Newtonian rheology that may occur.

10 CORRELATION OF THE PIPELINE PERFORMANCE CHARACTERISTICS WITH RESPECT TO THE PARTICLE SIZE DISTRIBUTION AND SLURRY CONCENTRATION

10.1 Introduction

The pipeline performance characteristics discussed in the preceding chapters clearly indicate that it is possible to transport many South African slurries at medium concentrations while some can be transported in paste form.

All the slurries investigated in this study are waste materials where the size distribution is determined mainly by the process involved in producing these products. This fact to a large extent determines the concentration that can be transported bearing in mind, that system optimization is not necessarily a factor in determining the transport concentration.

Of the various parameters involved in the hydraulic transportation in a pipeline, the particle size distribution of the solids forming the slurry plays a predominant role, because of its direct effect on the slurry rheology and maximum packing density and thereby on the friction loss along the pipeline and the critical deposit velocity.

The maximum concentration that can be transported is a basic function of the particle size distribution and the allied characteristics including the maximum packing density and the resulting rheological characteristics. It should be noted that the rheological characteristics are not solely dependent on the particle size distribution, but can also be influenced by additional characteristics such as particle shape, particle absorption and adsorption characteristics and the attractive or repulsive charges which may be present.

The maximum concentrations required and tested in this thesis are generally not based on an optimization of the transportation of these slurries but on the end requirement of the slurry at the exit of the pipeline. This is particularly the case in the various backfilling applications. Modification of the size distributions could thus possibly result in better performance characteristics, but is not considered in this thesis.

In general the medium phase slurries (up to 90% of the maximum loosely packed packing density) displayed a mixture of Newtonian and Non-Newtonian characteristics. The Non-Newtonian characteristics becoming more predominant as the particle size distribution of the carrier medium reduced in size and as the solids concentration increased.

All the medium phase slurries were characterised by critical deposit velocities, the value being a function of the particle size distribution, particle specific gravity, the prevalent rheology, the relative turbulence and the pipe size.

The dense phase pastes are characterised by high pressure gradients, low transportation velocities and general non-Newtonian characteristics. A limit to the flow of pastes and a transition to bed slip flow is a function of the percentage of micron-sized material and the homogeneity of the resulting mixture.

The correct use of the size distribution envelope and the minimum fines requirement facilitates the transportation of coarse material in a non-Newtonian carrier. Higher concentrations are possible with the introduction of the coarse material with beneficial effects from a pressure gradient point of view.

The performance characteristics of all the slurries and pastes transported are dependent on the maximum packing density, the particle size distribution and the homogeneity of the mixture.

The influence of these factors are discussed on a global basis in the following sections.

10.2 The General Relationships between the particle size distributions and the associated physical characteristics

The experimental results presented in chapters 7 - 9, show that the conveying characteristics of a medium and dense phase paste are largely dependent on the particle size distribution, the solids concentration, the bed-load component and the allied rheological characteristics.

Quartz based tailings slurries can be transported in a number of regimes at the same concentration. At $C_w = 67\%$ a tailings slurry with $d_{50} = 156$ µm will be transported as a mixed regime turbulent flow slurry while a slurry with $d_{50} = 39$µm will be transported as a laminar regime paste. The difference in the prevalent regime is influenced by a number of factors, which in general can be related to the particle size distribution and its associated characteristics.

The associated characteristics include:

1) the maximum packing densities, experimental and predicted
2) the surface area for particle wetting
3) the Newtonian/Non-Newtonian character and the associated absolute values of the rheology.

The above characteristics are dependent on the complete size distribution, but in order to illustrate the general trends, characteristic diameters are defined. The characteristic diameters utilised are the d_{10}, d_{50} and d_s values. The d_{10} and d_{50} values are based on the relative percentages passing a particular size, while the d_s value is based on the diameter which would result in half of the total surface area. The calculation is based on the following equation:

$$d_s = \frac{12}{\text{total surface area per kg x particle density}} \qquad (10.1)$$

The characteristic diameters, the maximum loosely packed volume concentration, the maximum predicted volume concentrations the surface area and the specific gravity of all the slurries tested are included in the following Table (10.1) for comparative purposes.

Table 10.1 Particle defined characteristics of the slurries tested

Slurry type	d_{10} (μm)	d_{50} (μm)	d_s (μm)	Surface area per kg of sample (m²)	$ø_{max\ exp}$ (%)	$ø_{max\ 1}$ (%)	$ø_{max\ 2}$ (%)	s.g (kg/m³)
Tails 1	5,8	34,9	28,6	155,0	-	-	80,8	2710
Tails 2	6,3	37,8	37,8	137,3	42,8	78,9	81,1	2780
Tails 3	5,0	21,2	25,6	174,6	45,1	77,7	82,7	2690
Tails 4	6,4	33,2	31,0	144,6	41,2	76,2	78,1	2680
Tails 5	19,3	77,7	73,7	60,6	46,6	72,2	71,8	2700
Tails 6	32,3	88,1	96,8	45,6	47,5	69,8	69,8	2720
Tails 7	16,0	78,8	59,5	74,7	46,8	74,3	74,6	2700
Tails 8	16,2	107,4	64,4	71,9	48,8	74,8	74,3	2590
Tails 9	7,1	73,8	39,1	118,9	44,4	79,2	79,9	2580
Tails 10	5,6	47,4	31,1	146,5	40,3	80,4	81,6	2630
Tails 11	1,9	15,0	14,6	262,5	51,5	77,8	86,2	3130
Tails 12	50,0	112,5	164,8	27,0	-	66,3	66,0	2700
Tails 13	5,7	30,3	26,2	168,9	-	78,2	82,2	2710
Tails 14	17,2	169,4	93,8	42,3	52,2	73,8	73,4	3021
Tails 15	175,9	264,0	515,9	8,6	-	64,9	65,0	2710
Tails 16	87,2	149,9	257,5	17,4	-	66,0	65,9	2680
Tails 17	39,5	156,9	96,3	45,6	47,6	72,6	71,6	2733
PFA 1	2,6	8,6	11,1	467,2	-	71,5	71,9	2230
PFA 2	4,8	32,1	26,6	202,0	46,1	78,9	80,9	2230
PFA 3	5,3	33,9	27,6	194,7	-	78,6	79,8	2230
HMC	105,7	139,0	284,7	9,6	-	65,5	66,2	4400
COAL	78,2	163,7	285,8	30,4	-	70,0	68,8	1381
DISCARD	1642	9000	6163	1,4	-	75,1	75,9	1381
CDW	485	7620			-	81,1	80,3	2710
BBA 1	212,0	4936	1548	2,5	-	81,2	78,4	3100
BBA 2	101,0	503,8	482,9	10,5	38,9	78,0	86,5	2360
CDW:RPT								
0,47 : 1	6,9	76,1	41,4	107,0	-	85,8	(105)	2710
0,96 : 1	8,2	199,5	54,9	80,6	-	88,5	(99,7)	2710
1,78 : 1	11,3	245,2	77,6	57,1	-	90,9	(95,2)	2710
BBA 1 : PFA 1								
1;9	1,9	10,8	13,4	391,8	-	77,5	(93,3)	2294
4:6	3,1	28,8	21,8	219,5	-	87,6	(116,0)	2512

Slurry type	d_{10} (μm)	d_{50} (μm)	d_s (μm)	Surface area per kg of sample (m^2)	$\phi_{max\ exp}$ (%)	$\phi_{max\ 1}$ (%)	$\phi_{max\ 2}$ (%)	s.g (kg/m^3)
Coal Mixtures								
Test 1	131,7	5092	1067,5	8,1	-	87,4	88,8	1381
Test 2	73,4	4435	674,6	12,9	-	84,4	95,7	1381
Test 3	60,1	2684	560,2	15,5	-	82,3	100,0	1381
PFA 2 : BBA 2								
1:1	11,7	145,0	59,3	88,2	-	83,9	94,3	2293
2:1	7,6	77,5	41,3	128,0	-	82,3	88,8	2272
4:1	6,3	55,6	35,8	148,8	-	81,5	83,1	2252

The relative influence of the particle size distribution on these characteristics are discussed in turn in the following sections.

The maximum packing density determines the maximum concentration at which a slurry can be transported, be it in paste form or as a sliding bed.

Two types of packing densities are utilised in this thesis, the experimental loosely packed density and the predicted packing density.

The basic relationship between the experimental packing density and the d_{50} and d_s is illustrated in Figure 10.1.

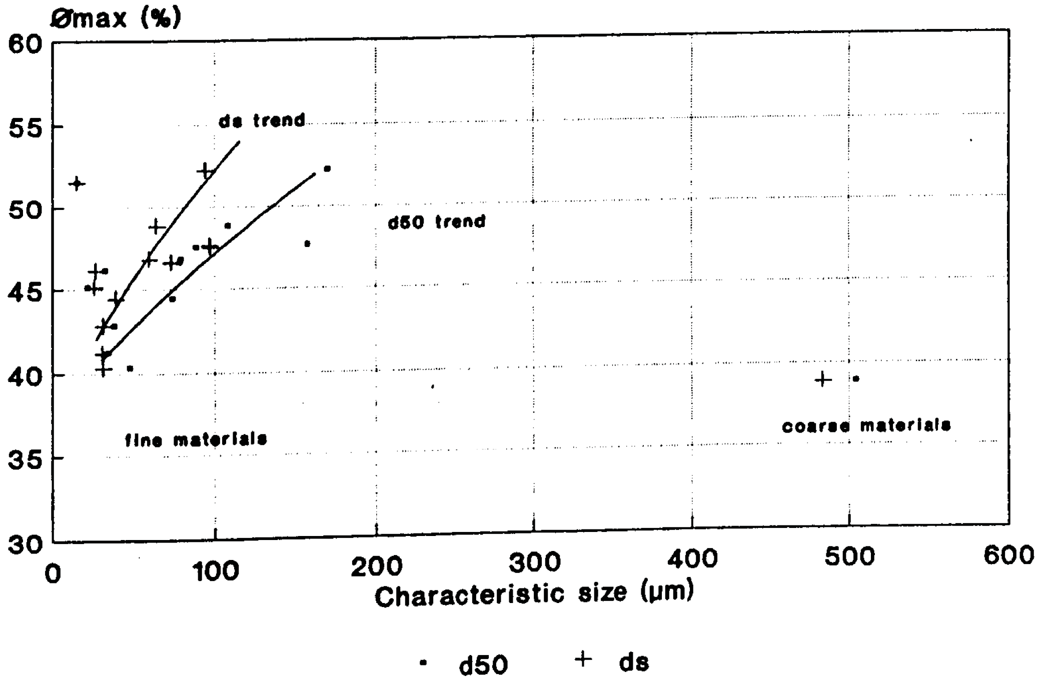


Figure 10.1 The relationship between $\varnothing_{max}$ and the d_{50} and d_s

In general there is an increase in the $\varnothing_{max\ exp}$ with an increase in both the d_{50} and the d_s. The trend is not absolute although the similar shaped and sourced tailings lie within a fairly close band. The different materials tested lie scattered around and generally above the quartz based tailings band.

The relationship between the experimental $\varnothing_{max\ 1}$ and $\varnothing_{max\ exp}$ is illustrated in Figure 10.2.

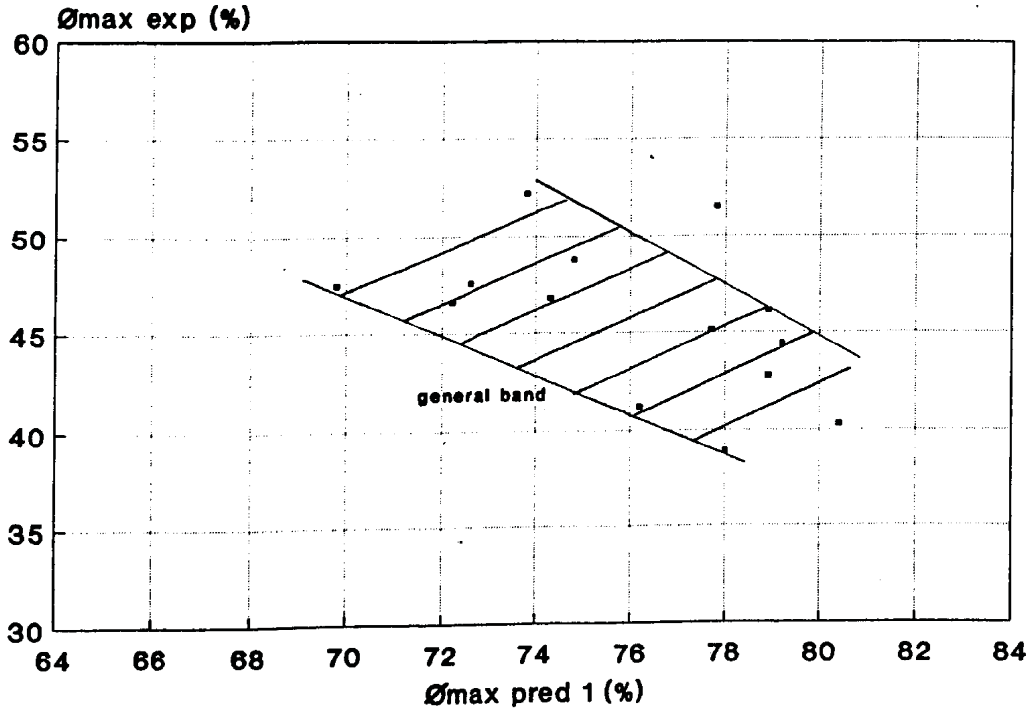


Figure 10.2 The relationship between $\phi_{\max 1}$ and $\phi_{\max \exp}$

The correlation between the experimental and predicted values, shows a general decrease in $\phi_{\max \exp}$ with an increase in $\phi_{\max 1}$. This trend is consistent with the trend observed by Dabak(95) and is also illustrated in Fig. 7.36 for tails 1 - 11. This general band, makes it difficult to use the predicted values for estimating accurately the maximum concentration at which a slurry could be transported. The $\phi_{\max}$ pred relationship with the d_{50} is even more scattered than the relationship with $\phi_{\max \exp}$ (Fig 10.3).

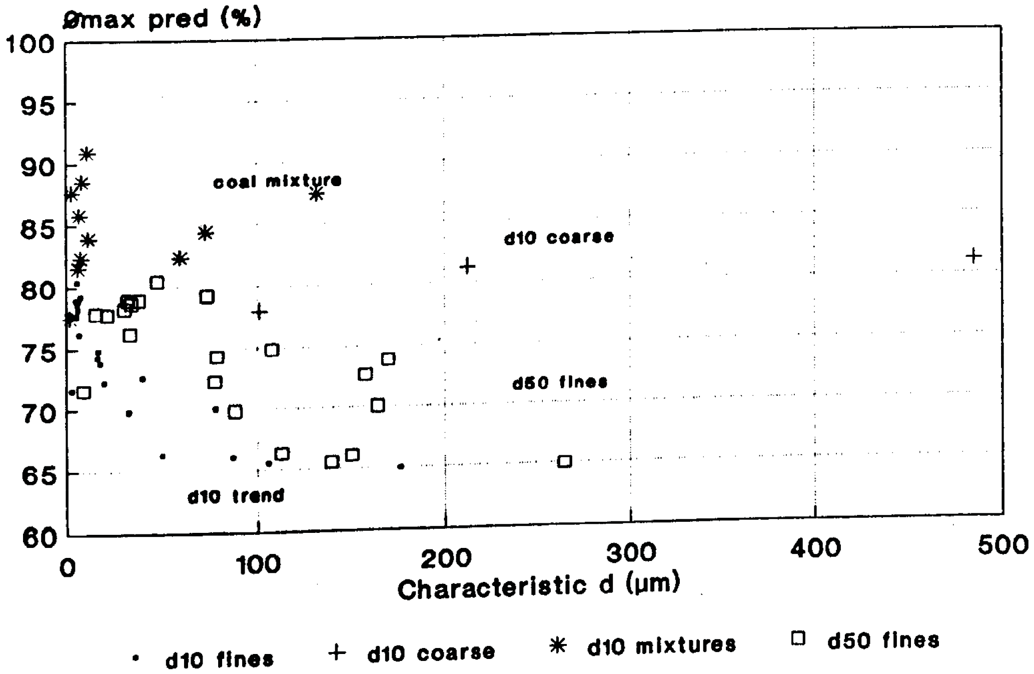


Figure 10.3 The relationship between $ø_{max\ 1}$ and the d_{50} and d_{10}

The trend established between the $ø_{max\ 1}$ and the d_{10} is more clearly defined than the trend with the d_{50}. The equation best fitting the $ø_{max\ 1}$ of the fine materials is given by:

$$SQR(ø_{max\ 1}) = SQR(-7{,}935E-2)*SQR(d_{10})+SQR(8{,}956) \quad (10.2)$$

The relationship between the d_{10} and d_{50} and the $ø_{max\ 1}$ for the mixture slurries is dependent on the mixture. In general however the predicted packing density increases with an decrease in the characteristic diameter (Figure 10.3).

Two different predictive methods are used to estimate the maximum packing density. The relationship between the two methods is illustrated in Figure 10.4.

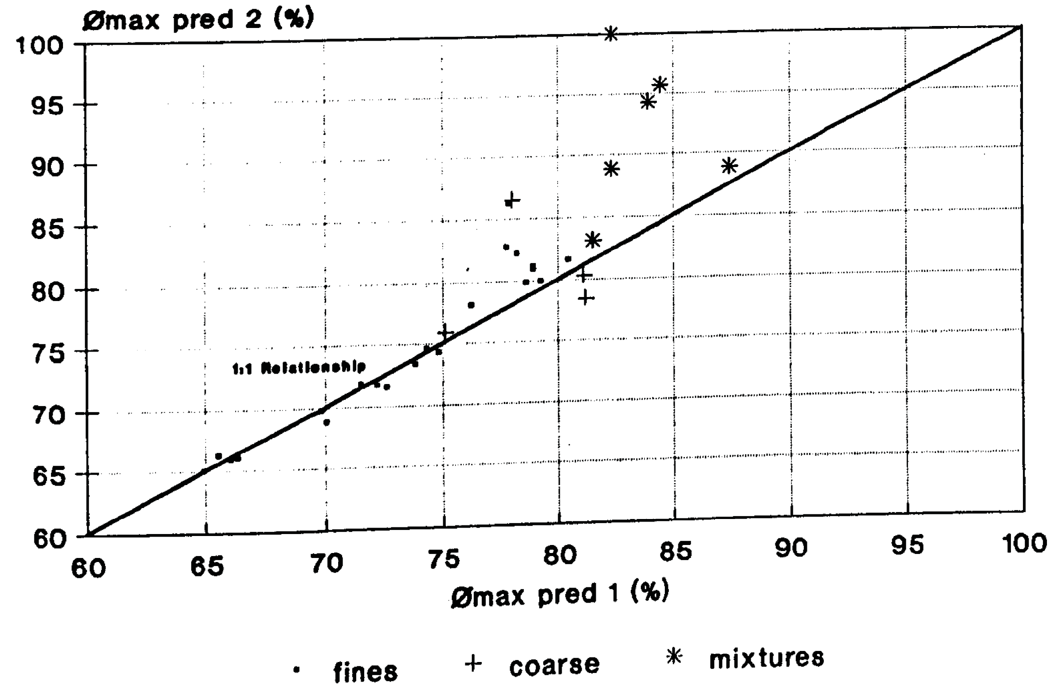


Figure 10.4 The relationship between $\varnothing_{max\ 1}$ and $\varnothing_{max\ 2}$

Several characteristics are evident. For the lower values of the predicted $\varnothing_{max\ 1}$ (<76%) a good correlation exists between the two predictive methods. Above $\varnothing_{max\ 1} > 76\%$ the relationship appears to be more scattered although they lie around and above the $\varnothing_{max\ 1} = \varnothing_{max\ 2}$ line. The second prediction method results in suspect values for the mixture slurries. The general methodology for obtaining the $\varnothing_{max\ pred}$ value is based on determining the minimum value of each row in the i.j matrix of particle size mixes.

Minus values are obtained for the RPT:CDW and the PFA1: BBA 1 mixtures. The lowest positive value obtained is given in Table 10.1. Two of the values are larger than 100% which would indicate that this method is not suitable for determining the predicted value of $\varnothing_{max}$ for mixtures.

The total surface area per kg of material correlates well with the d_{10} and d_s (Figure 10.5). The influence of this trend, although discussed with regard to the coarse material slurries (Sections 8.2, 8.4 and 9.6) is difficult to relate to the fine slurry performance characteristics without knowledge of the wetting characteristics of each product. The trend nevertheless indicates that more liquid is required to "wet" the finer materials, and therefore results in "thicker" slurries relative to the coarser slurries at the same concentration.

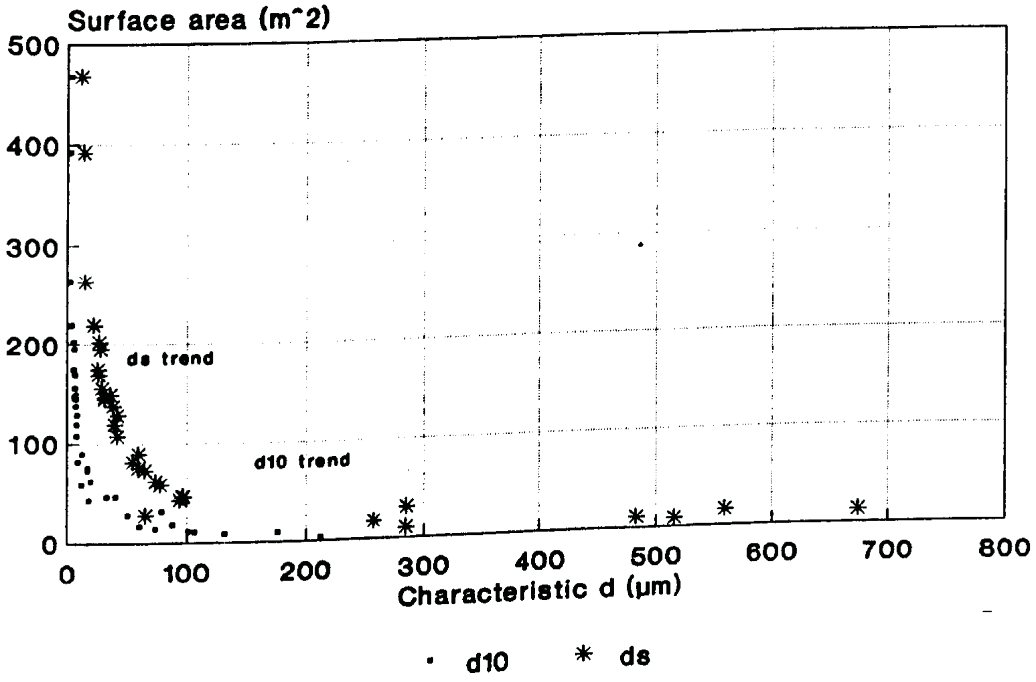
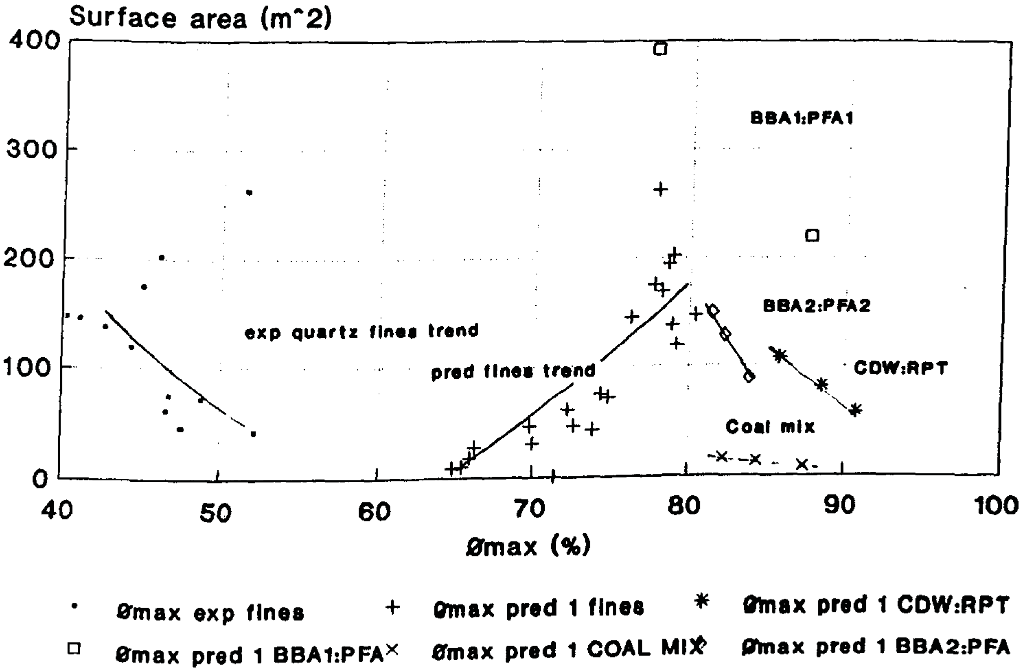


Figure 10.5 The relationship between the surface area per kg of material and the d_{10} and d_s

In general the surface area decreases with an increase in the d_{10} and d_s respectively. The equations best fitting the experimental points are given below.

$$LN(SA) = -0{,}8134\ LN(d_{10})+LN(661{,}47) \qquad (10.3)$$
$$LN(SA) = -1{,}011\ LN(d_s)+LN(4823{,}6) \qquad (10.4)$$

'he surface area can also be closely related to the $ø_{max}$ $_{xp}$ and $ø_{max\ 1}$ (Figure. 10.6).



igure 10.6 The relationship between the surface area per kg of sample and the predicted and experimental maximum packing densities

e surface area per kg shows a general decrease for an crease in $ø_{max\ exp}$ for the fines materials tested. The lationship is defined by the equation:

$$LN(SA) = -0,8134\ LN(d_{10})+LN(661,47) \qquad (10.3)$$

$$LN(SA) = -1,011\ LN(d_s)+LN(4823,6) \qquad (10.4)$$

The surface area can also be closely related to the $\emptyset_{max\ exp}$ and $\emptyset_{max\ 1}$ (Figure. 10.6).

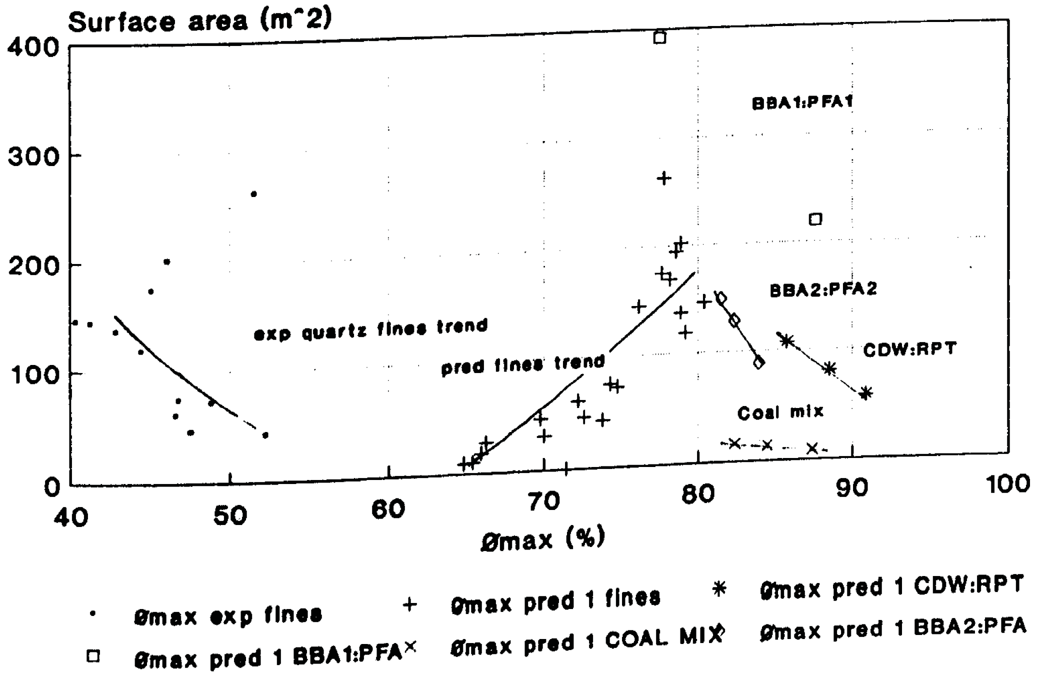


Figure 10.6 The relationship between the surface area per kg of sample and the predicted and experimental maximum packing densities

The surface area per kg shows a general decrease for an increase in $\emptyset_{max\ exp}$ for the fines materials tested. The relationship is defined by the equation:

$$LN(SA) = -2{,}975\ LN(\o_{max\ exp}) + ln(88{,}48) \qquad (10.5)$$

The opposite trend is illustrated for the fine materials when correlated with $\o_{max\ 1}$ (tails only):

$$LN(SA) = 13{,}33\ LN(\o_{max\ 1}) + LN(8{,}595E\text{-}24) \qquad (10.6)$$

The mixture slurries of coarse and fine materials, show a different trend to that shown by the fine materials. There is a general decrease in surface area for an increase in $\o_{max\ 1}$ with each mixture having its own definite relationship with $\o_{max\ 1}$.

The surface area of the waste materials forms an important component of the value of the rheology that can be expected as, the higher the surface area, the larger the amount of water required to wet the outside of the particles and the smaller the amount of free water available.

The characteristic size can thus be used to estimate a number of parameters, the best characteristic diameter to be used given in Table 10.2.

Table 10.2 Best characteristic diameter for estimating particle size related characteristics

Variable	Characteristic diameter	Relationship
$\o_{max\ exp}$ (%)	d_{50} d_s	$LN(\o_{max\ exp}) = LN(43{,}59)+7{,}73E\text{-}04*d_{50}$ $LN(\o_{max\ exp}) = LN(43{,}3)+1{,}17E\text{-}03*d_{50}$
$\o_{max\ 1}$ (%)	d_{10}	$SQR(\o_{max\ 2}) = SQR(-7{,}935E\text{-}02)*SQR(d_{10})$ $+SQR(8{,}956)$
Surface area per kg (m^2)	d_{10} d_s	$LN(SA) = -0{,}8134\ LN(d_{10})+LN(661{,}47)$ $LN(SA) = -1{,}011\ LN\ (d_s)+LN(4823{,}6)$

These relationships, if the particle size is known, can then be utilised to estimate the type and value of the rheology to be expected.

10.3 The general relationship between the type and value of the rheology with the characteristic diameter and the maximum packing density

In general the medium phase slurries displayed a mixture of Newtonian and non-Newtonian characteristics. The non-Newtonian characteristic becoming more predominant as the particle size distribution of the carrier medium reduced in size. These slurries all displayed settling characteristics, the critical deposit velocity being a function of the particle size distribution, the prevalent rheology, the slurry concentration and the pipe size.

The pastes all displayed non-Newtonian characteristics with no or limited settling characteristics.

The Newtonian/non-Newtonian character is related to the concentration, the particle size distribution and the maximum packing density.

The general relationship between the measured wall stress at a constant shear rate and the d_{50} and the experimental ϕ_{max} is illustrated in Figures 10.7 and 10.8 respectively.

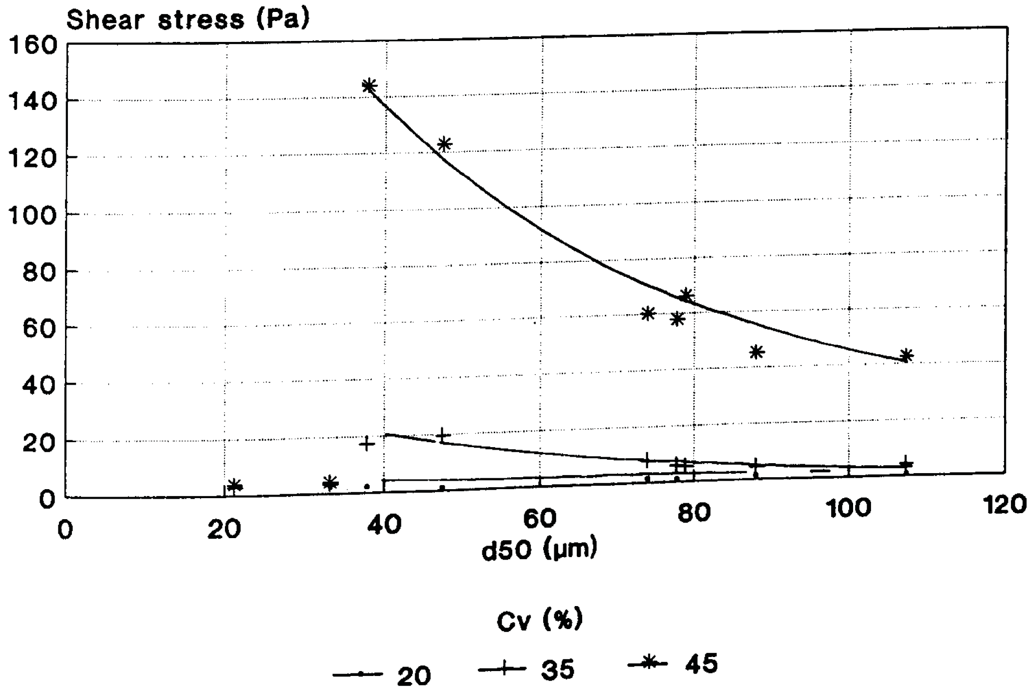


Figure 10.7 The general relationship between the measured wall stress and the d_{50} for constant volume concentrations and shear rate

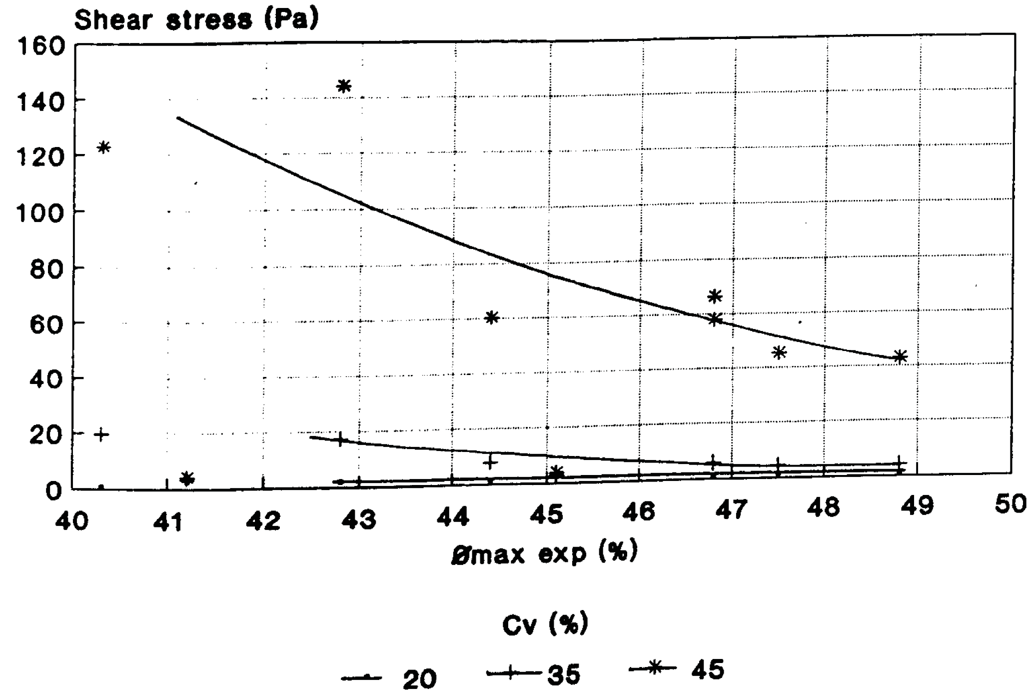


Figure 10.8 The general relationship between the measured wall stress and the $\varnothing_{max}$ for constant volume concentrations and shear rate

Both relationships have similar trends with increasing wall stress, with decreasing d_{50} and $\varnothing_{max}$ and increasing volume concentration.

The steepness of the curves is an indication of the non-Newtonian character of the mixture. At the lower concentrations the trend is linear indicating a Newtonian characteristic for all the slurries tested. As the volume concentration increases, the smaller diameter and lower packing density slurries move into the non-Newtonian regime, this trend being accentuated at the higher volume concentrations.

The above curves can be drawn for a number of constant shear rates. In this way the shear stress for a range of shear rates can be established. The resulting data can then be fitted to the yield pseudoplastic model to obtain the first estimate of the rheological parameters. It should however be stressed that it is preferable to conduct some form of viscometer test to obtain this data, as variables other than the particle size distribution can influence the type and value of the rheology for any particular slurry.

Once the rheology has been established, the appropriate predictive methods can be utilised to estimate the expected performance characteristics of the slurries (Section 10.6).

The rheology of the mixture slurries is more complex and difficult to estimate. An approximation of the carrier rheology can be made from the previously mentioned family of curves (Figures 10.7 and 10.8), once the excess water and volume concentration of the carrier has been established

The excess water available is determined by measuring the absorption and surface wetting characteristics of the coarse material and subtracting this quantity of water from the total present. This method has been shown to give a reasonable estimate of the prevalent rheology. The transport of coarse mixtures can however be complicated by the formation of a dilute annulus around the central core. The properties of this annulus are difficult to estimate and could possibly result in large errors, when using the above approach.

10.4 The transportation of medium phase slurries

The transport of a medium phase slurry is characterised by a number of parameters. A normal heterogeneous type slurry is characterised by the general features illustrated in Figure 4.2. As the physical values of the rheology increases, the tendency of the curve to flatten out and reach a minimum becomes less pronounced.

The non-Newtonian character of the medium phase slurries tested further enhances; the carrying capacity of these slurries, the reduction of the critical deposit velocity and the reduction of the pressure gradient in the region above the new critical deposit velocity. This result is more evident when transporting a coarse material in a non-Newtonian fines carrier (Figure 9.46).

The high speed flow of the medium phase slurries can be correlated to the rheological response measured for the slurry. Where strong pseudoplastic tendencies are evident, lower friction gradients in terms of the measured headloss (metres of fluid pumped per length of pipeline) can occur.

The conveying of medium phase slurries is generally limited to the pump capacity and the maximum packing density. The influence of the slurry rheology and concentration is illustrated in Figure 9.47. Positive displacement pumps can be utilized to transport these slurries, but the relative economics of both systems need to be established prior to the installation of a system.

10.5 The transportation of dense phase slurries in paste form

The transportation of a high concentration slurry in paste form is characterised by a number of features:

1) For a slurry to be transported in paste form it is essential that the mixture is a homogeneous non-settling mixture. To a large extent this is determined by the percentages of -50 µm material. For the quartz based tailings the limiting sizes to allow the formation of paste transportation appear to occur in the region of $d_{50} < 50$ µm and $d_{10} < 20$ µm. This limitation is however not absolute as variations within the size distribution together with the packing characteristics and various interparticle forces will ultimately assist in determining the final characteristics.

   Quartz based tailings with the characteristic particle sizes larger than defined above will generally be transported as a sliding bed.

2) The pressure gradients of pastes are mainly dependent on the rheology of the mixture and to a lesser degree on the flowrate of the mixture. The yield pseudo-plastic model is generally applicable to the pastes transported in this study.

3) Pastes are transported in the laminar flow region and can be transported at low velocities (of the order of 0,1 - 1 m/s).

4) The restart of a stationary paste pipeline is generally characterised by a gradual build up of the conveying pressure to the pressures normally associated with

conveying at the start up flowrate. Pseudo pastes or sliding bed slurries are characterised by the need for an excess pressure requirement to restart a stationary pipeline.

5) As the rheology is so dependent on the concentration and the particle size distribution, tight control measures are required to ensure the above are kept within the system limitations.

6) The coarse mixture pastes have lower pressure gradients than the fines only pastes. Furthermore the operating band of concentrations increases as the percentage of coarse material is increased. This increase in the concentration range is allied to the apparent increase in the predicted maximum packing density.

To be able to transport a slurry in paste form a number of requirements have to be fulfilled. These include :

1) The most important criteria for any fine material paste is the ability to form a homogeneous mixture, even when the paste is stationary. As previously stated, for the quartz based tailings this appears to be related to the -50μm and -20μm fractions.

   Two practical rule of thumb tests can also be utilised to determine the likely degree of homgeneity.

   The first test involves placing the mixture to be transported in the palm of the hand. If a fist is slowly clenched, then the homgeneity is established by the response of the mixture as pressure is applied to it.

If the mixture oozes out between the fingers during the application of the pressure, then the mixture will be transported as a paste. If the solids remain behind in the hand and only the water or a dilute slurry is squeezed out, then the slurry is likely to be transported as a sliding bed with possible problems occurring due to the non-homogeneous and settling nature of the mixture.

A further test can be accomplished by drawing a smooth surface over the mixture. If a smooth shining surface remains, then transport as a paste is possible. If the surface is dull with holes in it paste transportation is unlikely.

The above two rule of thumb tests are applicable to both the fines only and the fines and coarse mixtures.

2) The transport of coarse aggregates in a fines carrier in paste form is possible provided that certain limitations are not exceeded.

   i) The carrier itself should be pumpable in paste form
   ii) The coarse aggregates size distribution must lie within the boundaries of the respective top size pumping envelopes defined in DIN 1045. This becomes more critical as the percentage of fines decreases. In mixture pastes fines are regarded as the material less than 212 μm. The minimum percentage of fines for coarse/fines mixtures is of the order of 16% of the total mass of the solids.

There are generally insufficient fines available below this value to form a homogeneous mixture and blockages are thus generally the order of the day.

iii) Besides the minimum fines requirement, the water content should be regulated to ensure that the carrier medium is not too dilute as the fines carrier will then not bind and support the coarse material and segregation can then occur. The general band of volume concentrations that can be transported for the quartz based mixtures is of the order of 82% - 96% of the $\varnothing_{max\,1}$ value. For the BBA/PFA mixtures this range changes to 64% - 82%.

Too high a water content results in an unsaturated mixture which in the main is unpumpable and prone to blockages.

iv) It is important that prior to any paste being transported through a pipeline that the pipe surface is suitably "wetted". This is particularly important when coarse/fines mixtures are transported. This can be achieved by pumping a dilute fines only slurry or water prior to the mixture transportation. It is important to seperate the dilute carrier from the paste by some form of barrier such as a 'pig' especially if the paste is a coarse mixture.

10.6 The prediction of the performance characteristics of medium and dense phase slurries

The prediction of the slurry friction gradients for the medium phase slurries flowing in the mixed flow turbulent regime can be achieved through use of the modified 'wasp' model, provided that the correct rheology is utilised. This method as with most other methods, is not absolutely universal but will provide, as shown in this thesis, a reasonable prediction in most cases.

At the lower concentrations where the rheology approaches the Newtonian predictions of viscosity, marginal differences in the predictions occur if the Bingham, Yield Pseudoplastic or Newtonian flow models are used to predict the vehicle friction loss. This difference becomes greater as the non-Newtonian behaviour diverges from the predicted Newtonian behaviour.

For the medium phase slurries, the ideal approach to establishing the type of rheology is to conduct viscometry tests. If test work cannot be conducted then an initial estimate of the type of rheology and the maximum packing density can be obtained from the family of curves illustrated in Figures 10.7 and 10.8.

The laminar flow non-Newtonian homogeneous pastes are modelled well using the laminar flow equations for the generalised Bingham or yield pseudoplastic models.

A first indication of the rheology can be established from Figures 10.7 and 10.8 although as the relationship between the rheology and the particle size and maximum packing densities becomes more critical as the concentration increases, it is advisable to conduct viscometer tests.

The prediction of the critical deposit velocities of the medium phase slurries is not an easy task. In general the methods used in this thesis overpredict the critical deposit velocity. With the exception of the Thomas method

(Table 9.11) none of the other methods incorporate the effect of the changing rheology on the support characteristics of the vehicle. This reason would appear to indicate in general why over predictions occur.

In general the Thomas and Wasp predictions appear the more suitable for the finer slurries while the Durand approaches are more applicable to the coarse materials where the rheology is predominantly Newtonian.

10.7 Conclusions

The results and correlations included in this thesis has indicated the practical importance of the particle size distribution and its allied characteristics on the transport of medium and dense phase slurries.

The correlation of the rheological characteristics with characteristic diameters and maximum packing densities indicate that a general relationship occurs between these parameters. The general relationship band however furthermore indicates that other factors are prevalent in the final rheological make-up of the slurry.

The results of slurries tested indicates that particle size distributions with a $d_{50} > 130$ µm will generally have Newtonian rheology up to C_v's of 45%. Slurries with smaller d_{50}'s can be expected to exhibit non-Newtonian characteristics below $C_v = 45\%$, the smaller the d_{50} the lower the concentration at which non-Newtonian characteristics are evident.

In general the finer the material, the lower the maximum packing density and the lower the concentration at which non-Newtonian characteristics are evident, and the larger the likelyhood that a high concentration slurry can be transported as a paste. The percentage of -50µm and -20µm present also influence this characteristic.

The prediction of the maximum packing density using formuli derived from the packing of spherical particles does not result in a good correlation with experimental results. The experimental value is also dependent on the consolidation of the sample. Prediction of rheology based on maximum packing densities should take cognisance of the data available and the type of packing density utilised in the derivation of the formuli.

Knowledge of the d_{50} and maximum packing density facilitates the approximation of the rheology of the slurry for different shear rates, and derivation of approximate rheological constants. Where possible viscometer tests should however be conducted to validate the initial characterisation.

The non-Newtonian 'Wasp' method based on the turbulent flow Torrance equations, the laminar flow non-Newtonian models and the Hanks dynamic parameter appear to be suitable for the prediction of the performance characteristics of mixed regime medium phase slurries and dense phase paste, provided that the correct carrier rheology is utilised.

The inclusion of coarse material in a fines carrier has a mixed influence on the performance characteristics. In medium phase slurries, the inclusion of coarse material results in an increase of the critical deposit velocity and the pressure gradient in the zone surrounding the