tical and horizontal conveying of sand in the size range 0.3 - 1.0 mm and gravel up to a top size of about 8 mm using 79 mm diameter pipes. The specific energy consumption for the transportation of the coarse particles (2 - 5 mm) was found to be comparable with alternate means of hydraulic conveying. Current research has indicated that dense-phase flow is suitable for horizontal and vertical distances of about 1 - 2 km.

The transport of waste material to incinerators for the conversion of waste products to energy is gaining acceptance in Europe\(^\text{(18)}\). The waste material is fed as a paste into hot rotary kilns. The materials range in consistency from liquid to stiff plastic mixes. The transport of sugar beet sludges\(^\text{(19)}\) is another example of the application of high concentrations sludge transportation.

The examples cited above have indicated that it is possible to transport higher concentration slurries economically. The major parameters involved in these higher concentration slurries is a combination of the maximum packing density, the overall size distribution, the fines/water relationships, the overall concentration, the particle-wall relationship and the rheological parameters involved.

### 3.3 The development of medium and dense phase systems in South Africa

Although studies have shown that long distance transportation could be economical\(^\text{(13,20)}\) hydraulic transportation in South Africa is generally limited to pipelines varying in length up to 30 km.
Some of the major pipelines operating in South Africa are listed in Table 3.2.

Until the Simmergo pipeline was installed, the Ergo system was the largest pipeline system in South Africa. These systems transport slurry which is produced from the monitoring of the old slimes dams on the East Rand to central complexes, where uranium and gold are extracted from the slimes.

The systems listed in Table 3.2 are generally operating in the low to medium concentration range. Recent applications in specialist systems has led to research being conducted to investigate the transport characteristics of higher concentration slurries based on the principles listed in the previous Section. The major difference in the optimisation process of the systems is however different from that applied to the systems discussed in section 3.2 where optimisation of the overall system is based on the relative economies of the comminution, transportation and utilization phases. In the South African applications, the motivation for each system is based on different parameters and has led to the optimisation of the transportation characteristics within the appropriate confined constraints imposed on this phase.
Table 3.2 Hydrotransport systems operating in South Africa

<table>
<thead>
<tr>
<th>Location</th>
<th>Length (km)</th>
<th>Diameter (mm)</th>
<th>Throughput (tons/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reclaimed Gold mine</td>
<td>Variable</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Tailings</td>
<td>up to 18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERGO</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simmergo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daggafontein</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranium beary gold slime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Randfontein</td>
<td>10,2</td>
<td>155</td>
<td>40</td>
</tr>
<tr>
<td>Freddie South</td>
<td>11,1</td>
<td>406</td>
<td>332</td>
</tr>
<tr>
<td>Babroco Ellaton</td>
<td>19</td>
<td>155</td>
<td>51</td>
</tr>
<tr>
<td>Ellaton-Stilfontein</td>
<td>15,2</td>
<td>229</td>
<td>118</td>
</tr>
<tr>
<td>Phosphate slurry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Langerbaan</td>
<td>3</td>
<td>150</td>
<td>152m³/h</td>
</tr>
<tr>
<td>Poskor</td>
<td>3,6</td>
<td>162/192</td>
<td>542 - 9</td>
</tr>
<tr>
<td>Diatomaceous Ore</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Henkries</td>
<td>4,6</td>
<td>125</td>
<td>11,1</td>
</tr>
</tbody>
</table>

The systems incorporated and planned and which are the subject of this thesis are discussed in subsections (3.3.1 - 3.3.4).

A characteristic of the applications is the wide range of size distributions of the materials transported. These applications include hydraulic backfill in gold mines, power station ash removal, discard coal transportation and general waste disposal systems.
There is limited literature available correlating the various size distributions, particle specific gravities and concentrations of these mixtures. This research was initiated to compartmentalize, the performance characteristics of these South African applications according to their particle size distribution, maximum packing densities, specific gravities and concentrations.

The following brief description of some of these higher concentration systems attempts to outline, the basic systems, and the constraints imposed which dictate the performance characteristics of these slurries.

3.3.1 Backfill systems

At present the average depths of the deposits being mined in South African Goldmines are 2 000 m below the surface with the deepest workings in the industry being about 3 700 m. Future mining is planned at depths in excess of 4 500 m.

The current and expected depths give rise to two major problems, rock stress and heat. Conventionally the closure movement has been controlled by means of timber, concrete grillage supports and mat packs which are progressively compressed as the stope closes. However as more than 50% of all fatal accidents are caused by rock bursts and ground failure, the control of rock stress as depths increase is becoming more critical.

Although alternative options exist for coping with the above problems, the use of backfilling with hydraulically transported mine waste products offers an attractive solution.
The criteria involved in selecting the type of material utilised includes drainage rates of deposited material, immediate and long term support characteristics, effect of drainage water on the waste water balance within the mine and the economic implications of the plant necessary to get the backfill underground.

The major component of the slurry utilised in the backfill process is the fine silt sized reduction plant tailings (RPT) produced after the recovery of the gold and uranium. To achieve the necessary fill requirements and to satisfy the above criteria, several changes to the basic slurry can occur.

The major modification brought about in a number of applications is the removal of the fines component through a cyclonic operation. The primary motivation for this process is the enhancement of the material drainage characteristics. Further modifications to the slurry occur with the addition of binder materials and/or coarse material to enhance the strength characteristics of these slurries. The coarse material can be in the form of a sand with a top size of 2 - 3 mm or crushed development waste (CDW) rock with a top size of 30 mm. The RPT and rock products are angular in shape and because of their quartzitic nature are fairly abrasive.

The hydraulic system specifications are dependent on the varying transportation characteristics of the slurries transported\(^{(21,22,23,24)}\).
The basic fill slurries used are listed below:

1) classified tailings with or without a cementitious binder ($C_w = 60 - 65\%$)
2) dewatered tailings with or without a cementitious binder ($C_w = 65 - 75\%$)
3) milled waste rock ($C_w = 65 - 79\%$)
4) dewatered tailings aggregate mixtures ($C_w = 75 - 85\%$).

The basic systems used are illustrated in Fig. 3.1.

The dewatered tailings system (Figure 3.1(a)) utilizes some form of filter process i.e. belt or disc filter to dewater the tailings. The dewatered tailings are then remixed to the correct consistency and transported by high pressure positive displacement pumps to the stopes. Two basic options with regard to the location of the dewatering plant are used. The dewatering plant can be located on surface or underground with the tailings being gravity fed down to the dewatering plant. The latter system reduces the distances for high pressure pumping but is limited by the space available underground for the operation and maintenance of the dewatering plant.

The classified tailings system (Figure 3.1(b)) generally has the classification plant located on the surface. The underflow product is gravity fed to the stopes while the overflow product is pumped to the tailings dams on the surface.

The milled waste preparation plant (Figure 3.1(c)) is located underground and has the advantage that the waste material produced underground need not be hauled to the surface. Positive displacement pumps are used to trans-
port the milled slurries to the stopes.

The aggregate tailings mixtures (Figure 3.1(d)) are prepared above ground and transported by positive displacement pumps and gravity underground. A remixing station is located at the bottom of the vertical section as segregation within the column renders the mixture umpumpable. The wide range in material characteristics result in diverse performance characteristics\textsuperscript{(21,22,23,24)}.

All four systems are currently in use in South African gold mines.

Although only practiced to a limited scale, backfilling in coal mines offers a major growth area in the transportation of medium and dense phase fill slurries composed of pulverised fuel ash and boiler ash. At a symposium held on the utilization of ash\textsuperscript{(15)} it was submitted that the most effective way of disposing the large tonnages of ash that will be produced over the next century is by returning it underground to act as a backfill. It is estimated that by the year 2080 AD a total of 6,75 billion tonnes of ash will have been produced in South Africa.
Figure 3.1 Alternative backfill system options

The rationale behind the proposal presented at the symposium is as follows:

Modern mining methods can only achieve, on average, about 50% extraction of the available coal, the remainder being required to support the overlying strata to prevent cave-ins. Maximum extraction methods invariably cause surface subsidence of up to two metres, very often rendering the land unsuitable for certain types of farming due to the
resultant irregular topography and the formation of depressions in which runoff water collects. Underground aquifers are damaged or diverted by fissure formation and boreholes dry up, thus further impacting negatively on agricultural land which could be used for food production.

These negative environmental effects can be minimised or even eliminated by using ash to support the mined out workings and even more importantly, coal extraction could be increased beyond the levels achieved at present.

If the 6.75 billion tons of ash mentioned above could be used as backfill, the potential exists for releasing an equivalent amount of coal. At a selling price of R15 per ton, the coal released will be worth R101 billion. Furthermore, if the 250 million tons of ash currently accumulated at Escom power stations were used as backfill it would release coal valued at R3.7 billion, which is roughly the cost of a 3 600 MW coal fired power station.

Apart from the monetary value of the additional coal released, a considerable number of new jobs will be created and very importantly, South Africa will be making optimal use of one of its non-renewable natural resources.

A strategic plan is currently under consideration to determine the technical and economic feasibility of backfilling the mines with ash. Investigations have already been conducted to establish the pumping characteristics of high concentration PFA and PFA:BBA slurries(26,27).
3.3.2 Coal transportation

The stacking of coal at a South African mine posed several problems. These included the actual transportation of the coal from the sorting plant to a dump 1.6 km away and the internal combustion of the coal once stacked. The coal although of a high ash content and classified as discard coal can be burnt in the so called "new generation" power stations.

Previously this coal had been transported by truck and dumped on a central dump. A characteristic of these dumps however, is the internal combustion, within the dump which burns the stacked coal.

An investigation by the holding company of the mine in question revealed that if the coal could be stacked in a high density slurry form and compacted, then the conditions within the dump would prevent internal combustion from occurring.

The project required the mixing of a -50 mm discard coal to a -2 mm duff coal from the washing plant into a high density concentration slurry. The slurry concentration range which was dictated by the water content of the discard coal and duff coal slurry was in the range of 73 - 85%.

The successful completion of pumping trials\(^{28}\) of the high concentration coal slurry, led to the installation of a 1.6 km, 200 mm diameter system at the mine.

The advent of sanctions, and the inability of the plant to produce sufficient fines, has however unfortunately
resulted in the mothballing of the system. The pumping trials nevertheless indicated the viability of the system.

The transport of high concentration coal slurry fuels into coal fueled power stations currently being applied in the Belovo-Novosibirsk pipeline also has potential for application in the South African power-generation industry.

3.3.3 Overland waste disposal of ash (BBA and PFA)

The effective disposal of both pulverised fuel ash (PFA) and boiler bottom ash (BBA) is a major consideration in the design of any coal-fired station. The problems facing South African engineers are compounded by virtue of the fact that coal with high ash contents, is available at relatively low prices. As such, distinct from power stations in the rest of the world, South African power stations generate large quantities of ash.

It is not uncommon to find that on average a large 3600 MW power station such as Matla and Duvha burning 14 500 000 tons of coal per year with an ash content of 25% produces 2 650 000 tons/year waste product. Matla produces the following waste products on a daily basis:

- 10 000 tons of water
- 2 000 tons of BBA
- 10 000 tons of PFA

Ash is disposed of with two basic disposal systems, a 'wet' system and a 'dry' system. With the dry systems, the PFA is conditioned and transported to the ash dam by belt conveyor.
The 'wet' systems have traditionally been dilute slurry systems. Table 3.3 gives the salient features of some of the disposal systems currently in operation.

**Table 3.3 Wet ash disposal systems currently in operation**

<table>
<thead>
<tr>
<th>Station</th>
<th>Type of material</th>
<th>Pipe diameter (m)</th>
<th>Pipe length (km)</th>
<th>Design flow velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camden</td>
<td>PFA &amp; BBA</td>
<td>3</td>
<td>3.74</td>
<td>2.67</td>
</tr>
<tr>
<td>Matla</td>
<td>PFA &amp; BBA</td>
<td>3.5</td>
<td>2.90</td>
<td>2.96</td>
</tr>
<tr>
<td>Grootvlei</td>
<td>PFA &amp; BBA</td>
<td>3</td>
<td>2.60</td>
<td>2.67</td>
</tr>
<tr>
<td>Hendrina</td>
<td>PFA &amp; BBA</td>
<td>3</td>
<td>2.32</td>
<td>2.67</td>
</tr>
<tr>
<td>Komati</td>
<td>PFA &amp; BBA</td>
<td>3.12</td>
<td>2.3</td>
<td>2.67</td>
</tr>
<tr>
<td>Arnot</td>
<td>PFA &amp; BBA</td>
<td>3</td>
<td>1.98</td>
<td>2.67</td>
</tr>
<tr>
<td>Kriel</td>
<td>PFA &amp; BBA</td>
<td>3</td>
<td>1.90</td>
<td>2.67</td>
</tr>
<tr>
<td>Duvha</td>
<td>PFA &amp; BBA</td>
<td>3.5</td>
<td>1.78</td>
<td>2.67</td>
</tr>
<tr>
<td>Ingagane</td>
<td>PFA &amp; BBA</td>
<td>3</td>
<td>1.45</td>
<td>2.67</td>
</tr>
</tbody>
</table>

A common feature of the above disposal systems given in Table 2.3 is the low transport concentrations, 0 - 10% and 0 - 20% for the BBA and PFA slurry respectively. Furthermore BBA and PFA are transported separately. Developments in ash disposal systems, with higher concentrations is generating wide spread interest in Australia(29).

Disposal problems at Matla power station have resulted in Eskom re-evaluating their wet disposal process. The original system was designed to transport a $C_w = 20\%$ slurry. Each boiler has separate but parallel facilities.
for moving the BBA and PFA.

Due to the unexpected slagging characteristics of Matla coal, the amount of water needed to move the solids increased enormously. The available dam site is unable to handle the extra water and is resulting in excessively turbid return water which is resulting in further operational problems.

Furthermore as the existing dam is located above the nearby coal mine, Eskom considered relocating the present dam.

As Escom wished to, at the same time, reduce their consumption of water, research was initiated to establish whether the ash could be removed as a \( C_w = 50\% \) slurry.

The research work (Section 9.7)\(^{30,31}\) has indicated that it is possible to transport PFA:BBA mixtures at 50\% in a ratio of 1:1, 2:1, 4:1 in the same pipeline. The 50\% limit although initially set by the limitation of the mixing technology currently available at Matla has proved to offer an acceptable safe transportation concentration bearing in mind the rheology of the PFA carrier and the estimated ratios of BBA to PFA.

The research has led to tender documents being issued by Eskom for the Matla retrofit for final adjudication early in 1990.

Successful application of this technology, believed to be a world first, holds promise for massive water savings at other wet Eskom power stations.
3.3.4 General high concentration disposal systems

As part of a water conservation program at Jwaneng Diamond Mines in Botswana, a research project was conducted to establish the merits of a thickened tailings disposal system.

Jwaneng Diamond Mine is situated in the arid Kalahari region of Botswana. The principle source of water for the mine and surrounding town is an aquifer basin, 50 km north of the mine. This basin is considered to have a finite reserve as little recharging originates from atmospheric precipitation.

The largest loss of water within the mining operation is through the tailings disposal systems. The fine tailing product is transported as a 25% slurry by mass to the slurry impoundment dams. Some of the water associated with this product is recovered by decantation at the centre of these dams. A large proportion of the water is lost in this impoundment through evaporation. Of the $245,9 \times 10^3$ m$^3$/month of water supplied to the mine approximately 85% is lost through the slimes disposal system.

A water and energy balance for the mine based on the current disposal system and a thickened tailings disposal system is given in the following table.
3.3.4 General high concentration disposal systems

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A water and energy balance for the mine based on the current disposal system and a thickened tailings disposal system is given in the following table.
Table 3.4  Comparison of a 800 dry tons/hr thickened tailings and conventional disposal system\(^{(32)}\)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Conventional disposal system (CS)</th>
<th>Thickened tailings disposal system (TS)</th>
<th>% Reduction ((CS-TS)/CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_w (%))</td>
<td>30</td>
<td>60</td>
<td>-100</td>
</tr>
<tr>
<td>Slimes Flowrate (m(^3)/hrs)</td>
<td>1 950</td>
<td>736</td>
<td>62</td>
</tr>
<tr>
<td>Recycle water flowrate (m(^3)/hr)</td>
<td>1 456</td>
<td>242</td>
<td>83</td>
</tr>
<tr>
<td>Total volumetric flowrate (m(^3)/hr)</td>
<td>3 406</td>
<td>978</td>
<td>71</td>
</tr>
<tr>
<td>Slimes pipeline I.D. (mm)</td>
<td>609</td>
<td>381</td>
<td>37</td>
</tr>
<tr>
<td>Recycle water pipeline I.D. (mm)</td>
<td>432</td>
<td>178</td>
<td>59</td>
</tr>
<tr>
<td>Mass (cost) of pipe system (kg/m)</td>
<td>131</td>
<td>50</td>
<td>67</td>
</tr>
<tr>
<td>Nett power for horizontal slurries transportation (kw/km)</td>
<td>22,2</td>
<td>21,8</td>
<td>2</td>
</tr>
<tr>
<td>Nett power for vertical slurries transportation (kw/km)</td>
<td>6,6</td>
<td>3,3</td>
<td>50</td>
</tr>
<tr>
<td>Nett power from horizontal recycle water transportation (kw/km)</td>
<td>49</td>
<td>17</td>
<td>61</td>
</tr>
</tbody>
</table>
The encouraging figures revealed by the above study resulted in a comprehensive investigation of the dewatering characteristics and the transportation of thickened kimberlite slurries\textsuperscript{(32)}. The research work was completed, and led to the construction of a pilot dewatering and pumping plant at the mine. Indications of high operating costs for the dewatering have however recently reduced interest in this project. Other diamond mines have nevertheless expressed interest in the technology developed.

A major problem has developed at the Vergenoeg mine in the Northern Transvaal with the disposal of the haematite tailings produced at the mine. The thick sludge is oozing from the existing slimes impoundment dam into the river. The environmental controls in South Africa have however dictated that this sludge be removed from the river and transported to an alternative site. The haematite tailings has a top size of 564 µm and a \(d_{50}\) of 15 µm. Successful pumping trials on the sludges at concentrations in the range of 80 - 95\%\textsuperscript{(33)} has resulted in this high concentration disposal system being considered for moving the offending product from the river bed.

The disposal of a high concentration asbestos tailings slurry has been considered\textsuperscript{(34)}. This waste product is made up of asbestos fibres and crushed waste rock. The average \(d_{50}\) of the waste rock is in the region of 450 µm, while the asbestos fibres are on average 10 - 15 mm long. Test-work has shown that this waste product can be transported at concentrations of 60 - 65\%. The top range is dictated by the lack of "flowability" at this concentration and the need to force feed the pumping cylinders.
Middelburg Steel and Alloys factory in Middelburg produces fine and coarse ash products. A total of 15 tons of ash is produced daily with the coarse ash forming from 3.5% to 14.5% of the total production. The d$_{50}$ of the fine and coarse ash is 6 µm and 24 µm respectively. The waste product is currently transported to a dump site 1 km from the plant. Slurry test loop investigations$^{(35)}$ have shown that the fine ash and mixtures of the bottom ash and fine ash can be transported in dense slurry form at concentrations of 66% – 79%. The small quantities of ash produced however result in small pipe sizes with corresponding high pressure gradients which makes this system uneconomical when compared with a more dilute slurry system and the transportation system currently utilized. Economic application of this technology is however possible at steel plants producing larger quantities of ash.

The medium and dense phase systems listed have indicated the growing world wide interest expressed in this form of transportation. Further advancement of these systems, especially in South Africa are however at this stage limited by the general wariness of the 'unknown' performance characteristics of higher concentration slurries.

The main aims of this thesis has thus been:

1) the characterization of the performance characteristics of the medium and high density slurry applications identified in South Africa, in terms of the particle size, its allied characteristics and the solids concentration.
2) Identification of design procedures for designing these systems and,
3) Practical demonstrations of the technology to dispel the general wariness for these higher concentration slurries.
4 REVIEW OF EXISTING TECHNOLOGY

4.1 General Classification of Slurries

In general the flow characteristics of solid-liquid mixtures differ from that of Newtonian fluids. Reasons for this include:

1) Superimposed on the various properties of the liquid are the properties of the solid particles as well as the effect of the particles on the mixture properties.
2) The particular flow conditions will contribute to the flow characteristics.

In broad terms slurries can be categorised by the influence of the materials carried by the slurry on the carrying medium. The following categories exist:

1) Where the liquid retains its normal flow properties and carries along relatively large or heavy particles.
2) Where the solids may be small or light and be suspended without seriously affecting the liquid flow properties.
3) Where very small solids at high concentrations result in a completely homogeneous slurry of properties markedly different from normal liquids.
4) Where large particles are carried at high concentration by interparticle contact and carried by a fluid that retains its normal characteristics.
5) Where large particles are carried in a homogeneous medium of small particles of properties markedly different from the original liquid.

Categories 1 and 2 are conveniently grouped under the heading of settling slurries whilst those in the remaining
categories are classified as non/slow settling or mixed regime slurries.

4.2 Flow of Settling Slurries

Settling slurries can be further categorised into the flow regimes which occurs as follows:

1) pseudo-homogeneous flow  
2) heterogeneous flow  
3) saltation  
4) moving bed

4.2.1 Pseudo-homogeneous flow

This slurry is categorised by a uniform concentration and velocity profile across the section of the pipeline through which it flows (Fig. 4.1). This is more closely defined by the equation\(^1\).

\[
C/C_A > 0.8
\]  
\[-(4.1)\]

The response of the homogeneous suspension on a log plot of the pressure gradient versus the flowrate is similar to that exhibited by a single phase fluid (Fig. 4.2).

The transition from laminar to turbulent flow is sensitive to the system rheology and Reynold’s number\(^1\).

4.2.2 Heterogeneous flow

The distribution of solids in the pipe section is not uniform but increases towards the bottom of the pipe. The characteristic pressure gradient response is categorised by
a minimum pressure gradient value. This minimum may, but does not necessarily correspond to the minimum deposition velocity. At velocities below the minimum value, the particles will start falling out of suspension and be transported along the bottom of the pipe.

Heterogeneous slurries are generally described by

\[
\frac{C}{C_A} < 0.1
\]  

-(4.2)

---

**FIGURE 4.1** Flow regimes of settling slurries
In heterogeneous flow systems, particle inertial effects are prominent as opposed to homogeneous mixtures where the rheology of the system is the dominant factor.

For large particle slurries the definition of the particular flow regime, heterogeneous or pseudo-homogeneous, is to a large extent dependent on the flow velocity. For a slurry composed of small and large particles the definition is based on the velocity and rheology of the system.

4.2.3 Saltation (Fig. 4.1)

Once the particles have dropped out of suspension, they will move with consecutive bounces along the pipe bottom.
4.2.4 Sliding bed/stationary bed (Fig. 4.1)

Once deposited the particles will slide along the bottom of the pipe. A further reduction of the flow velocity will often result in a pipe blockage.

4.2.5 Mixed regime slurries

As slurries transported in industry and the mining sector generally have a broad particle size distribution the flow of a slurry may have a combination of the regimes listed above.

A mixed regime slurry is generally described by\(^1\)
\[
0.1 < C/C_A < 0.8
\]
\[-(4.3)\]

A number of the empirical and mechanistic approaches to determining the operating regimes of a slurry make use of this equation to split the flow of slurry into the various components viz, heterogeneous pseudo-homogeneous and bed load (Section 5.5).

4.3 Flow of Non-Settling Slurries

4.3.1 Introduction

In this category non-settling slurries and dense phase slurries can be divided up into several categories.
Figure 4.3 Slurry categories

The various categories are characterised briefly by definition of their salient features in the following sections.

4.3.2 Newtonian fluids

Newtonian fluids are characterised by a single variable, i.e. viscosity. The governing equation for a Newtonian fluid is given by

\[ \tau = f (\frac{du}{dy}) \]  

which can be simplified to
\[ \Gamma = \mu \left( \frac{du}{dy} \right) \]  

This proportional ratio experienced in a Newtonian fluid is illustrated in Figure 4.4.

![Newtonian fluid rheogram](image)

**Figure 4.4**  Newtonian fluid rheogram

### 4.3.3 Time Independent Non-Newtonian Flow

For time independent fluids in laminar flow the shear stress is a function of the applied rate of shear

\[ \Gamma = f \left( \frac{du}{dy} \right) \]

The governing function is governed by at least two parameters, depending on the type of slurry.

The responses of the different slurries are illustrated in Figure 4.5 and by the general governing equations listed below\(^{(1)}\).
Bingham
\[ \Gamma - \Gamma_y = \eta \left( \frac{du}{dy} \right) \] ---------(4.6)

Pseudoplastic
\[ \Gamma = k \left( \frac{du}{dy} \right)^n \quad n < 1,0 \] ---------(4.7)

Ostwald-de-Waele
\[ \Gamma = k \left( \frac{du}{dy} \right)^n \quad n > 1,0 \] ---------(4.8)

Dilatant
\[ \Gamma = k \left( \frac{du}{dy} \right)^n \quad n > 1,0 \] ---------(4.9)

Yield Pseudo-plastic
\[ \Gamma - \Gamma_y = k \left( \frac{du}{dy} \right)^n \quad n < 1,0 \] -----(4.9)

---

**Figure 4.5** Time independent non-Newtonian fluids

**4.3.4 Time dependent Non-Newtonian fluids**

The generally accepted responses of time-dependent fluids are illustrated in Figure 4.6.
Figure 4.6  Shear diagram for time-dependent fluids

The classical definition of a thixotropic fluid is illustrated by the hysteresis loop in Figure 4.6. Although the above definition is useful to identify the presence of thixotropic behavior, it provides little direct value with respect to the pipe flow of the fluid.

The description of the behavior of a thixotropic fluid at each of several durations of shear is generally more applicable (Figure 4.7).
Figure 4.6  Shear diagram for time-dependent fluids

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The description of the behavior of a thixotropic fluid at each of several durations of shear is generally more applicable (Figure 4.7).
Figure 4.7 Stress-time and stress-strain response of a thixotropic fluid\(^{(38)}\).

In these discussions a thixotropic fluid is one that experiences structural decay with time under a constant sustained shear. A thixotropic fluid is also often considered to be a yield-pseudoplastic whose properties change with the time applications of shear, ultimately approaching equilibrium or limiting values.

Rheoplectic fluids exhibit a reversible shear thickening with time and are illustrated in Figure 4.6.

4.4 Dense phase high concentration slurries

The previous descriptions of non-settling flow are based primarily on mixtures of small particles. The concept of a non-settling slurry can however be extended to include a range of size distributions which may be classified as a settling slurry at low concentrations. This is achieved by increasing the overall concentration such that particles are no longer free to settle.
In general a multisized slurry will settle out at a critical deposition velocity. As the concentration is increased the physical mechanisms involved on the deposit velocity are as follows:

1) At low concentrations or low viscosities, deposition occurs under turbulent flow conditions with the height of the sliding bed being only as great as the viscous sub-layer thickness. Consequently deposition occurs at a low velocity. As the viscosity is increased the transition regime rises up to the transport velocities of interest. When this happens the turbulent support of particles is reduced and the bed height increases.

2) At still higher viscosities pure laminar flow is obtained. At this stage the bed height is determined by the insitu solids concentration and is much higher than that which was present under turbulent flow conditions and can be obtained only if the viscosity is raised sufficiently high.

Dense phase slurries can thus be prepared in one of three ways:

1) A dense phase slurry can be made up by introducing discrete particulate solids into a carrier fluid so that \( C_v \) attains a value of about 60%. The particles (100 - 10 000 \( \mu \)m) retain their identity during transportation and are not cohesive or liable to form complex non-Newtonian mixtures.

2) Fine particles can be mixed together to form a non-Newtonian mixture at high concentrations.

3) By introducing coarse particles into a fine particle non-Newtonian carrier, resulting in essentially a homogeneous non-Newtonian mixture.