



University of Miskolc



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**RHEOLOGICAL INVESTIGATION OF FLY ASH – LIME –MINE WATER
MIXTURES IN ROTATIONAL RHEOMETER FOR THE DEVELOPMENT OF
HYDRAULIC BACKFILLING TECHNOLOGY**

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Statement of Originality

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Abstract

The mining of sulphide ore at the Mátraszentimre mine ceased in 1986. Since then, acid mine water has been produced by the "acid rock drainage" (ARD) method. In order to prevent further damage, the previous mine had to be permanently closed. While technology for the backfilling of fresh fly ash has been developed, the Mátra Power Plant, which produces fresh fly ash, will soon cease production. As a result, the utilization of previously deposited fly ash is now mandated. Old fly ash-lime-mine water mixtures must be analyzed for their rheological properties in order to develop backfilling technology. In a rotational rheometer, mixtures of fly ash, lime, and mine water (FLM) will be subjected to rheological testing to achieve the study's primary objective. This will allow for the progression of hydraulic backfilling technology.

Using a rotational rheometer, the rheological properties of a mixture of fly ash, lime, and mine water were evaluated. This equipment measured both shear rate and shear stress. The Mátra Power Plant samples of fly ash were taken. In addition, sulphide mine water, calcium oxide (CaO), and carbide lime (KM) were also obtained. Moreover, the moisture content, particle size distribution, and particle density of the fly ash were analyzed because these variables are crucial to the development of the proposed technology. Due to the experimental rheological properties, the filling slurry's thixotropy, yield stress, and plastic viscosity were significantly altered, indicating that an increase in the amount of fly ash had a significant effect on these properties. Additionally, the FLM mixture's rheological properties were identical to those predicted by the Bingham model. The performance of the slurry developed as a result of increasing the concentration of fly ash. The nearly identical trend of the generated curves indicates that the age of the fly ash has no bearing on its utilization in backfilling technology. This conclusion is supported by the experimental data. Both newly produced fly ash and fly ash with a longer history can provide the necessary properties for the advancement of backfilling technology. Even if the company that produces sulphide no longer has access to a source of fresh fly ash, it can still continue the backfilling process by utilising older fly ash.

Keywords: fly ash; mine water; rotational rheometer; Bingham model; thixotropy; yield stress; shear stress; plastic viscosity; lime.

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CHAPTER 1. INTRODUCTION

1.1 Background

The GyöngyöSOROSZI underground base-metal mine is located 100 km East of Budapest, within the Mátra Mountains, close to Gyöngyös town. The annual production of the mine was 100-150 kt of low grade Pb-Zn ore (ca. Pb+Zn 4% grade) (Faitli et al., 2010). However, the operation of the mine was halted in 1985, while the water drainage stopped in 1986. The entry points to the mines (excluding one that warrants drainage) were plugged in 1988. Final shutting down of the mine requires backfilling of a section of the mine openings, as high convergence of pyrite (FeS_2) causes the acid rock drainage (ARD) interaction at that space. The responsible organization chose to backfill the mine with fly ash from power plant exceptionally close, therefore application of the fly ash is on-going.

Delivering the ideal material characteristics of the old fly ash is a significant issue confronting the sulphide ore mining company. Information in regard to the rheological conduct of fly ash slurry is important to set up the most proper backfilling technology. The challenge existing with the tailings is the management of the older fly ash, deposited years back, which has not been used for the backfilling aimed at limiting the effects on the environment. The sulphide mine containing residual sulphides oxidates sulphides to yield the ARD, which leads to the considerable pollution of both underground water and surface water. The responsive sulphide ore mine can be steadied through the integration agents such as fly ash, cement, lime, and organic matters (Lottermoser, 2010).

In their earlier research, Iyer and Stanmore (2000) demonstrated that the rheology of a fly ash-lime-mine water (FLM) suspension is affected by a variety of factors, including particle size, surface properties, mineral constituents, solid content, pore fluid chemistry, and chemical additives. On the other hand, the rheological investigation of fly ash that has been combined with mine water and lime as an additive has only gotten a small amount of attention in the field of research. Fly ash from coal is typically utilised as a by-product due to the fact that it is cementitious and alkaline (Lee et al., 2017). Stanmore and Page (1992) used a vane approach to estimate the produce strain of abundant fly ash slurries. They articulated that the stress produced per time increased in accordance with the pozzolanic response of the precipitated calcite. Mahlaba et al.

(2011) found that the less viscous the fly ash paste was, the higher the salinity of the fly ash paste. They arrived at this conclusion by observing the concentration of saline fly ash paste. Simon and Grabinsky (2013) investigated the superficial yield stress of paved stakeouts for paste with fly ash. They found that the apparent produced pressure increases as fly ash concentration increases due to increased particle closeness in parking. This was the conclusion that they came to after conducting their research.

In this study, the FLM mixture shear stress-shear rate is determined using different concentrations of the fly ash, mine water, and lime. The additives used in this study were Calcium oxide (CaO) lime and Carbide lime (KM). Additional variables that were also subjected to investigation included temperature, mixing time, and additive concentration. The present study permits an in-depth conception of the wet mixture, time effects, and rheology temperature of FLM, which is critical for the development of the backfilling technology.

1.2 Problem statement

In 1986, the mining of sulphide ore was halted at the Mátraszentimre mine, which is located in Hungary. Since then, a process that is known as "acid rock drainage," or ARD, has been producing acidic mine water. This water is produced as a result of the mine oxidation process. It is imperative that the operation of the old mine be terminated for good. Despite the fact that a hydraulic backfilling technology that makes use of fresh fly ash had been developed, it has been decided that it is necessary to make use of fly ash that was deposited at an earlier time. This decision was reached after it was ascertained that the utilisation of fly ash that was deposited at an earlier time is required. On the other hand, the Máttra Power Plant, which was the main contributor of fresh fly ash, is going to be shut down. An investigation into the rheological properties of the old FLM mixture is necessary because its rheological behaviour plays an important role in the process of developing backfilling technology.

1.3 Research objective and significance

The finding of this study will be essential to mining industry that intend to apply the backfilling technology, where fly ash forms part of the backfilling material. The need to ensure environmental sustainability and protection from the deposition of tailings from mining companies makes this

study critical, since it opens opportunities for tests of other tailing materials suitable for backfilling. Specifically, this study finds its direct relevance and importance to the sulphide mining company, that purposes to apply earlier deposited fly ash tailings as a backfill material. Moreover, this study will also be essential for application by the Government of Kenya, Ministry of Petroleum and Mining that has been witnessing increasing incidences of abandoned, used and disused mines collapses. The used, disused, and abandoned mines in Kenya pose serious health and safety risks, which have resulted in a number of lives lost and several injuries reported. Additionally, the impacts of ARD on the surface and underground water has been reported to cause serious health complications in the communities the mines were located. The government through relevant agencies will thus be able to employ the tailings in developing suitable backfilling technologies.

The company Nitrokémia Ltd. commissioned the Institute of Raw Material Preparation and Environmental Processing, University of Miskolc to reconsider the existing hydraulic backfilling technology of the Mátraszentimre mine in the beginning of 2021 (Institute of Raw Material Preparation and Environmental Processing, 2021). Systematic investigations are ongoing. I have worked in this project, my duty was to carry out the rheological tests, and therefore the main objective of this research is to undertake rheological investigation of FLM mixture in rotational rheometer for the development of hydraulic backfilling technology. Determining the rheological characteristics of the FLM mixture is critical to ensure effectiveness of the purposed backfilling technology development.

The following specific objective was also determined:

The effect of fly ash, lime, and mine water quantity by mass (volume) variation in the mixture in determination of the shear stress and shear rate of the mixture.

CHAPTER 2: LITERATURE REVIEW

2.1 Final mine closure technologies

Activities surrounding mining of underground minerals for economic purposes has led to the onset of voids of different shapes such as caves, gob empty structures, stopes and even goaf (Sheshpari, 2015). These subversive vacuums lead to unsteadiness risks for mining of nearby columns, overhead structures, and the users of the nearby mining area, which may exhibit financial natural resources, or settling peril for foundations on the underground through previous activity, or after excavations are abandoned. Along these lines during chronicled improvement of mining innovation, few strategies for topping off or backfilling for those voids have been created. A portion of the normal techniques for inlaying which are utilized by monetary factors and further objectives such as improvement of mine or leaving the coal mine are silica alumina-based backfill, hydraulic backfill, and cemented paste backfills. The following subsections highlights the different backfilling techniques that have been in use.

2.1.1 Hydraulic backfill method

The hydraulic embankment is characterised by the utilisation of water as a mode of transport for the conveyance of hydraulic backfilling materials for the purpose of obstructing excavated holes such as stopes (Sheshpari, 2015). Figure 1 illustrates an example that is relevant to the discussion. As a result, the entry openings to the excavation have been blocked off with merged bulkheads and a drainage system to enable water to drain out of the stope. Backfill material that has been hydraulically yielded is emptied into the stope through the fill opening in the head of the stope. The height of the hydraulically driven backfill material is extended, which results in an excessive accumulation of water on the refill topping. In addition to this, all of the water should be drained through various channels, such as bulkheads, drainage water, or tapped water.

Hydraulic backfill exhibit the following properties, extreme element magnitude is under $1\text{ }\mu\text{m}$ and remarkably smooth elements are taken out to make penetrability in the backfill substances. Hence those elements that exhibit sizes that are equal or less to $10\text{ }\mu\text{m}$ need to be under 10% and even lesser than that altogether (Sheshpari, 2015). Slurries for hydraulic refill have masses ranges of 40-50% (Solid areas capacity). It is recommended that the penetrability of hydraulic backfill solid

be between 10⁻⁵ and 10⁻⁶ metres per second. However, gravity is used to extract excess water from the backfill material, and this process is supported by drainage that occurs away from the backfill. The absorbency of the hydraulic backfill that has been placed is fifty percent, and it has been accounted for that its permeability rate is thirty percent (Sheshpari, 2015). Paved or unpaved hydraulic backfill are both viable options; however, paved hydraulic backfill is more likely to be the most cost-effective excavation strategy in situations with a low waste particle size and a small amount of waste.

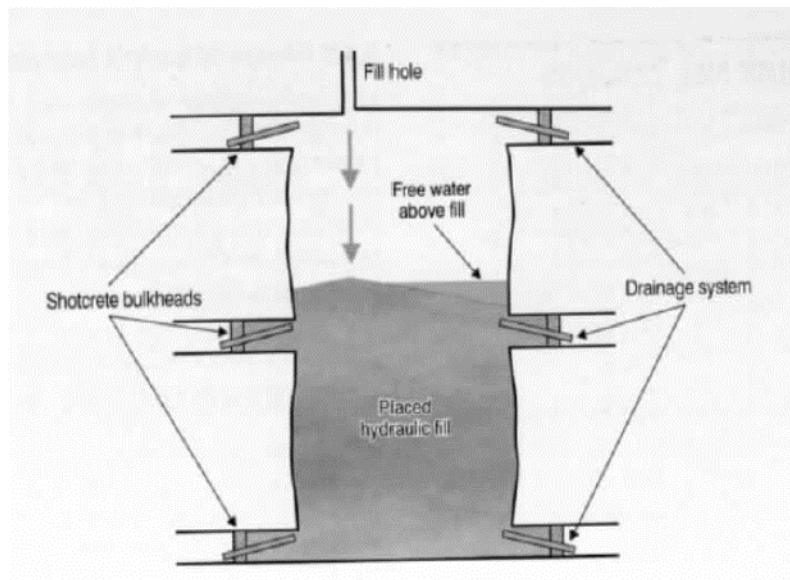


Figure 1 Showing the hydraulic backfilling of an open stope, indicating the drainage system critical to ensure water drainage out of the backfilled stope (Sheshpari, 2015)

2.1.2 A Novel Silica Alumina-Based Backfill

Yao and Sun (2012) conducted research on an innovative silica alumina-based backfill material that was fabricated from coal refuse and fly ash. The most recent reports on industrial development indicate that the coal industry is one of the fuel industries that is growing at the quickest rate. As a result, the coal industry generates a significant amount of waste in the form of coal refuse. When fly ash and coal refuse are subjected to a variety of thermal activation temperatures, such as 20 °C, 150 °C, 350 °C, 550 °C, 750 °C, and 950 °C, they demonstrate a wide range of characteristics (Sheshpari, 2015). Alternating between 20 °C and 950 °C, the thermal activation temperature is

constantly adjusted, which greatly improves the viscosity and pozzolanic properties of coal refuse. On the other hand, the viscosity of fly ash is significantly reduced in stimulation temperatures above 550 °C due to intense agglomeration conditions on its surface (Yao & Sun, 2012). Figure 2 illustrates how coal refuse and fly ash behave in terms of their flowability and strength when subjected to varying levels of thermal stimulation at innumerable temperatures. It was possible to develop an improved strategy for the material used for backfilling, such as using 5 percent coal refuse heated to 750 degrees Celsius and 15 percent fly ash heated to 20 degrees Celsius in the stimulated percentage. According to the findings of the research conducted, this optimal ratio in backfill material offers the highest comprehensive strength, the lowest bleeding rate, and the best flowability (Sheshpari, 2015).

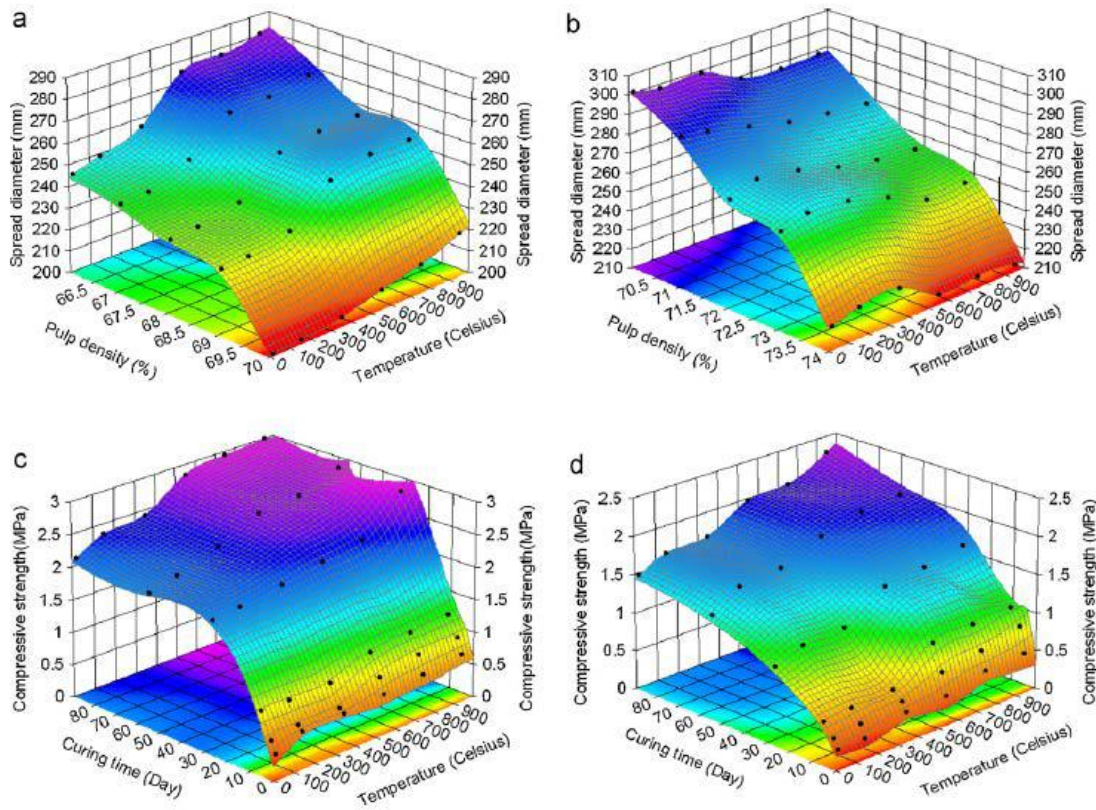


Figure 2 Showcasing flowability and strength properties of coal refuse and fly ash in varied thermal stimulation temperatures (Sheshpari, 2015)

According to Yao and Sun (2012) study, toughened backfill building was subjected to test in distinct spaces for poisonousness discharging properties, however, no tested substances exceeded

the Environmental Protection Agency (EPA) restrictions, a clear depiction that silica alumina-based backfill material is environmentally friendly. Only 1% of cement was included to the investigated silica-alumina backfill material, and the remaining components of the material were manufacturing compact leftover, which highlights immense latent in saving the investment costs in the backfill industry.

2.1.3 Cemented paste backfill method

Cemented paste backfill (CPB) refers to a non-homogenous material that is produced by combining waste stakeouts, water, and concrete. Approximately 70 to 85 percent of waste solids are added to the pile, and either clean water or excavated and treated water is used, while 3 to 7 percent of the total weight is added to the pile as a hydraulic binder. According to Sheshpari (2015), CPB proves to be among the leading backfilling technologies currently in use and preferred in mining industries, which has proved to provide impeccable and safe working underground working conditions in underground mines apart from its known environmental benefits. Preserved and toughened CPBs used in stopes develops reinforced pillar type ground aimed at supporting the adjoining excavation process in underground mines and safe operations for the mining workforces in the subversive excavates (Sheshpari, 2015).

2.2 Rheological behaviour of dispersed systems/ Rheological Models

The rheology of a material moving is mostly illustrated by the connection identified amongst the material shear stress and the shear strain rate, often referred to as a rheogram or flow curve. A pertinent example of a flow curve is shown in Figure 3. Newton's law of viscosity is the commonly and widely known rheological model since it corresponds the shear rate and stress via the constant of proportionality known as the absolute viscosity (Irgens, 2014). Furthermore, the viscosity is a common property that is utilized to characterize the flow curve slope. Those components that are not compliant with the Newton's law of viscosity are therefore referred to as non-Newtonian. A good example, in mineral suspensions, which require extensive base shear stress for its component disfigurement and flow. Such behaviour demonstrated by mineral suspensions is referred to as plastic. However, in a non-linear flow curve, the aspects of shear thickening and thinning is mostly identified in components subjected under flow conditions (Lemm & Malkin, 1994). The prior

happens when the velocity increases with cumulative shear proportion, while the later represents differing behaviour.

Several logical concepts are in existence in literatures for the estimation of rheological properties of the fly ash slurry as shown in Table 1. A significant number of the proposed models are either theoretically or empirically produced, but majorly centres on the investigational facts of a specific component (Lemm & Malkin, 1994). Additional models possess expounded probability but also abhors limitations whose figures must be acquired analytically, depicting that not exact incorporated model or estimate procedure has been established with general use.

Table 1 Rheological models and parameters

Rheological model	Constitutive equation	Rheological parameter
Newtonian	$\tau = \mu \cdot \gamma$	μ – <i>absolute viscosity</i>
Bingham plastic	$\tau = \tau_o + \eta \cdot \gamma$	τ_o – <i>yield stress</i> η – <i>plastic viscocity</i>
Power law	$\tau = K \cdot \gamma^n$	K – <i>consistency index</i> n – <i>exponent</i>

Rheology of disseminated systems is an essential processing attribute. Having the option to illustrate and control the behaviour of dispersions, one has the ability to warrant their optimal performance. The rheological characteristics of dispersions specifically those with higher contents of solids, are multifaceted and sturdily reliant on the functional forces (Irgens, 2014). The addition of particles, on the other hand, not only causes the hydrodynamic disturbance of the flow, which results in an increase in the viscosity of the liquid, but it is also the leading cause of nonconformity from Newtonian behaviour, which includes shear rate dependent viscosity, elasticity, and time dependent rheological behavior (Lemm & Malkin, 1994). Colloidal dispersions typically behave similarly to shear-thinning liquids, also known as low viscous liquids, when they have a volume

fraction that is in the moderate range. However, when the concentrations are high enough, the dispersions take on the characteristics of solids and frequently demand a certain amount of stress in order to distort the physical system before they will start to flow.

The microstructure that has been deformed as a result of stress typically is unable to recover from large strains immediately because the colloidal interactions that govern the microstructure have a short range that decreases as the interparticle parting increases (Irgens, 2014). However, in conditions in which the connections between particles are attractive, loose flocs with fractal structures can form. This leads to a greater volume fraction of active particles and, as a consequence, an increase in viscosity. Above a certain volume fraction, a sample-spanning network forms, which causes the material to behave in a manner similar to that of a gel while also producing an apparent yield stress. By breaking up and recovering floc structures, shear-induced thixotropic behaviour is produced. If the particle concentration is lower than the maximum packing fraction, then electrostatic or steric repulsion between particles defines an excluded volume. This results in a crystalline or gel-like state (Lemm & Malkin, 1994).

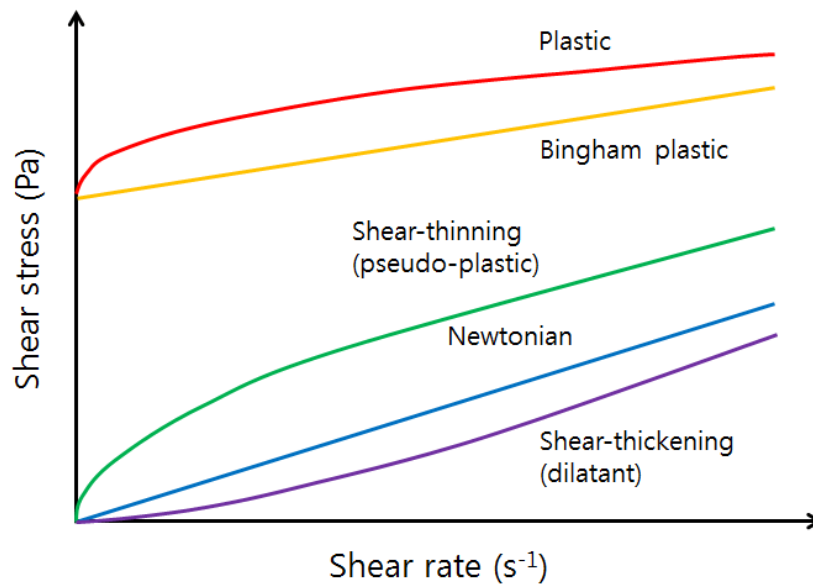


Figure 3 Showing different material behavior under distinct models of rheology. The red curve is known as the yield pseudoplastic (Lemm & Malkin, 1994)

Understanding the behaviour of fluids under different Rheological models is critical to help in conceiving a property of the FLM mixture. Developing the backfilling technology is critical since

the material (fly ash) under use will be subjected to shear force. Therefore, understanding the behaviour of the FLM mixture is vital to help in correct identification of the parameters suitable for the backfilling technology. Hence, Newtonian, Non-Newtonian, Power law, and Bingham models will be discussed in the subsection below.

2.2.1 Newtonian and Non-Newtonian

Newtonian and non-Newtonian fluids are two main fluid groups and is necessary to distinguish them to apply the correct model. Newtonian fluids obey a single model having a constant viscosity for any shear rate, or in other words a lineal relation exists between shear rate (γ) and shear stress (τ), a constant ratio τ/γ (Irgens, 2014). This ratio is called absolute viscosity (μ). Air and water are Newtonian fluids under normal circumstances (Idahosa et al., 2014).

$$\tau = \mu \cdot \gamma \quad (1)$$

Fluids that do not follow the Newton's linear law are called non-Newtonian fluids. They do not have a constant viscosity or absolute viscosity, so a viscosity function or variable is defined as the apparent viscosity (η). Shear stress for non-Newtonian fluids is given by:

$$\tau = (\gamma) \quad (2)$$

2.2.2 Power law model

Power law is among others, a fluid model used to predict non-Newtonian behaviour. Its equation can be expressed in function of shear stress.

$$\tau = K \cdot \gamma^n \quad (3)$$

where K is the steadiness parameter, and n is the power law index. If $n < 1$ then the power law describes a pseudoplastic fluid. If $n > 1$ then, the power law describes a dilatant fluid. Figure 4 below shows a graphical representation of a power law model.

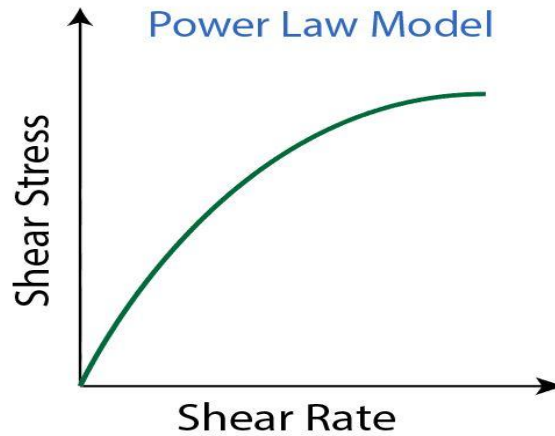


Figure 4 Curve representation of power law model in determining fluid rheological parameters, shear stress against shear rate (Irgens, 2014).

Dilatant and pseudoplastic fluids shall be explained below.

The viscosity of fluids is dependent on temperature, shear rate and time. We already have seen that classification of viscosity relies on the shear rate, shear strain or both (viscous, elastic and viscoelastic). Secondly, we analysed the connection between shear rate and shear stress, if it is lineal or not (Newtonian and non-Newtonian). Now, the fluids dependence of time shall be explained. Inside the purely viscous fluids, it means that we have shear rate dependence, two types of subclassification are established. When the viscosity is not affected by the time the fluids are called time independent, and time dependent when the viscosity changes with time.

2.2.3 Bingham plastic fluid

A material is regarded to be Bingham if it resists stress it is subjected to, but after a yield stress is surpassed, it flows as a viscous fluid. In most cases, such characteristics are exhibited by emulsions, foams, suspensions of solids in liquids, and slurries. Fluids that obey Bingham model are referred to as Bingham plastic fluids. The behaviour of the materials demonstrates a linear correlation between shear stress and shear rate once an initial magnitude of shear stress has been determined. The plastic viscosity is depicted in Figure 5 as the slope of a line, with the yield point serving as a representation of the threshold stress. The Bingham plastic model is characterised by the equation that is presented below;

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (4)$$

where, τ is shear stress, $\dot{\gamma}$ is shear rate, τ_0 is minimum yield stress (threshold stress), μ is plastic viscosity.

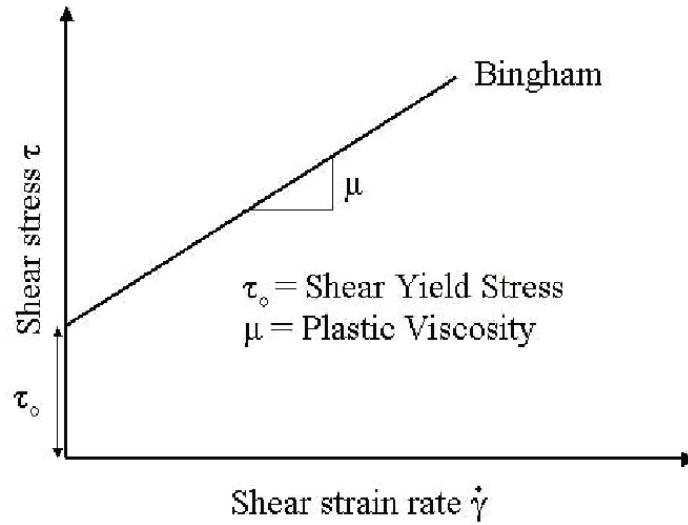


Figure 5 Bingham plastic fluid curve representation showing the different parameters making up the Bingham equation (Irgens, 2014).

2.3 Time dependent and time independent fluids

A fluid is regarded as time dependent when the shear stress increases or decreases with respect to time at an equal shear rate. The fluid gains its initial properties after sometime to stop the fluid movement. In the event the shear stress increases, the fluid is referred to as Thixotropic, while if it decreases, the fluid is named Rheopectic. Critical examples of thixotropic fluids encompass margarine, grease, or printing ink. A good example of rheopectic fluid is gypsum paste.

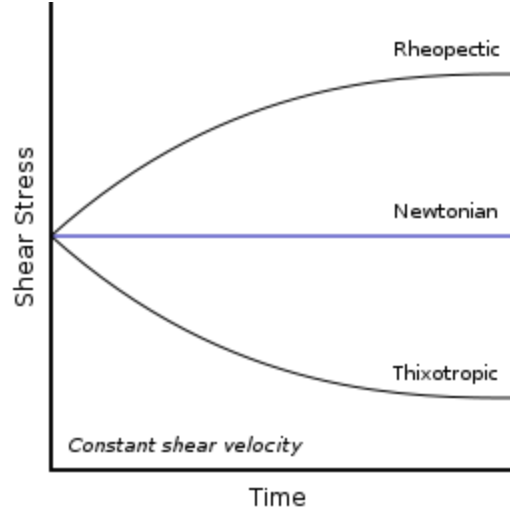


Figure 6 Curve representation of Time dependent fluids (Irgens, 2014).

Time independent fluids could comprise of dilatant fluids, viscoplastic or pseudoplastic. Viscoplastic fluids require minimal amount of shear stress to commence fluid behaviour. This minimum shear stress is also known as yield shear stress (τ_y). If the shear stress is lower than the yield shear stress, the material will have a solid structure while maintaining an elastic behaviour. This particular material is well suited for treatment with Bingham fluid. As long as the yield shear stress is exceeded and flow begins, the model operates under the presumption that the material will continue to behave in a Newtonian fashion.

$$\tau(\gamma) = [\tau_y + \eta\dot{\gamma}] \quad \text{where } \dot{\gamma} \neq 0, \quad (6)$$

$$\tau(\gamma) \leq \tau_y \quad \text{where } \dot{\gamma} = 0 \quad (7)$$

Pseudoplastic fluid also known as shear-thinning fluid behaves as a viscous fluid but with the characteristics that its viscosity decreases with increasing shear rate (Lee et al., 2017). This is a real typical case showcasing non-Newtonian fluids. In most cases, it can be seen in polymer, dispersions, and emulsion solutions. On the other hand, dilatant fluids sometimes referred to as shear-thickening fluids are found in a small group of genuine fluids that acts oppositely than the pseudoplastics (see figure 7). Its apparent viscosity increases with increasing shear rate (Irgens, 2014).

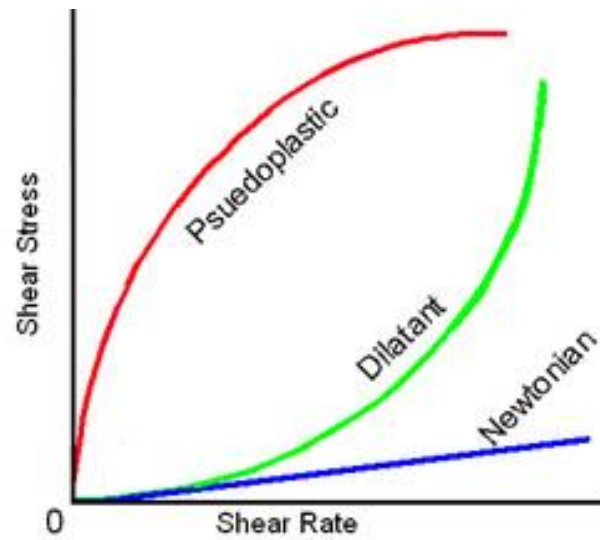


Figure 7 Pseudoplastic, dilatant, and Newtonian fluids curve representation (Qi et al., 2015)

2.4 Viscous-Viscoelastic Behaviours

Exposed to an applied force, an elastic solid immediately disfigures. The disfiguration is completely recuperated with the removal of the force. Conversely, the deformity of a viscous fluid increments with time when a force is applied. With the disengagement of the force, a viscous liquid stops to disfigure further, yet any earlier deformation remains (Willenbacher & Georgieva, 2013). A viscoelastic material displays both elasticity and viscosity. Exposed to an applied force, it deforms and its disfiguration increments with time, i.e., it creeps. At the point when the force is eliminated, just halfway deformity is recuperated promptly. It recuperates more, yet not all, of its deformation as time advances. Contingent upon the time size of interest, a viscoelastic material could act solid like or liquid like or a mix of both (Lee et al., 2017).

2.5 Rheological measurement methods

Determination of backfilling material rheological properties is critical for effective design and development of the backfilling technology. Additionally, it is also significant for utmost selection of the backfilling material, and material data with the aim of ensuring appropriate attainment of the stability of the backfilled mine. Relevant backfilling material properties can augment the efficiency of the backfilling technology as well as ensure that the stability of the backfilled mine is guaranteed and eliminate any potential danger in the form of mine collapse after backfill. This

section thus highlights the rheological measurement methods such as tube rheometer, falling sphere viscometer, and cylinder-cylinder rotation rheometer. This study used cylinder-cylinder rotational rheometer to determine the FLM mixture properties.

2.5.1 Falling Sphere Viscometer/ Hoppler Viscometer

A falling sphere is what the viscometer uses to measure the substance's viscosity. The amount of time that passes before the falling sphere reaches the next marking is measured and recorded. Both the sphere's density and its radius are already established facts. In addition, the liquid that is used is a recognised standard liquid; more often than not, it is water, which has a density of 1g/cm^3 . The Hoppler viscometer is illustrated here in Figure 8. Rheometers that use falling spheres are the most accurate instruments for determining the viscosity of Newtonian fluids. They are not reliable for determining the viscosity of fluids that do not follow the Newtonian model.



Figure 8 Falling bob viscometer (<https://www.jankiimpex.com/>)

The viscosity of the measured fluid is then determined using the equation:

$$\mu = K (\rho_b - \rho_s) t \quad (8)$$

Where μ : fluid absolute viscosity;

K : ball geometric parameter;

ρ_s : referenced liquid density;

ρ_b : ball density;

t : time

2.5.2 Tube rheometer

The principle of tube rheometer measurements is the laminar pipe flow, where the pressure loss has to be measured as a function of the flow rate. From this data the constitutive equation can be determined.

Regarding the construction of tube rheometers, the challenge is that small velocity but high-pressure laminar flow has to be set up in the measuring pipes. A rigid characteristic screw pump can be applied for this task. Practically, the developed tube rheometer is a small diameter pipe hydraulic loop, where the suspension is continuously circulated. The transport capacity and pressure range of the rigid characteristic screw pump and the pressure transducers were precisely matched for the measuring pipes and for the generally tested materials. The application of appropriate measurement protocol for the tube rheometer is very important. There are built-in mixing pipe sections in the developed tube rheometer to ensure the consistency of the mixture. The filled fine suspension has to be circulated with high flow rate to set turbulent flow in the measuring pipes and then the revolution of the screw pump can be lowered to set laminar flow.

When it comes to measuring the rheology of fine suspensions, the tube rheometer is by far the most accurate instrument. In order to properly apply the measurement principle, straight horizontal pipes must first have stable laminar flow established in them, and then pressure loss as a function of flow rate must be determined (Faitli & Gombkot2015). Researchers Willenbacher & Georgieva (2013) explain Newtonian incompressible fluid flow in horizontal straight pipes using laminar flow. A linear profile of shear stress is predicted by the Hagen-Poiseuille model, while a parabolic profile is predicted by a parabolic profile of velocity. Since the first derivative of the velocity is proportional to the shear stress, it makes sense that the shear stress is proportional to it. In order to describe laminar Newtonian flow, the Hagen-Poiseuille equation can be written as follows;

$$\frac{\Delta p \cdot D}{4 \cdot L} = \mu \cdot \frac{8 \cdot v}{D} \quad (9)$$

$$\tau_w = \frac{\Delta p \cdot D}{4 \cdot L} \quad (10)$$

$$\gamma_w = \frac{8 \cdot v}{D} \quad (11)$$

The shear rate of neighbouring layers and the shear stress are indirectly measured using viscometers and rheometers that have defined surfaces. A tube rheometer uses this layer, which is shaped like a cylindrical tube and consists of fluid molecules inside the pipe's inner wall. By measuring the pressure loss, it is possible to calculate the wall shear rate (γ_w) and the wall shear stress (τ_w). The wall shear rate can be calculated by taking the tangent of the velocity profile at the pipe wall. The well-known linear constitutive equation based on Newtonian physics is incapable of describing non-Newtonian rheology (Faitli et al., 2017). The results of the tests that will be presented later suggest that the Bingham plastic rheological model needs to be described in greater detail.

Non-Newtonian fluids may produce different velocity profiles in the tube rheometer than those described by Hagen-Poiseuille, and as a consequence, the $8v/D$ term may not be equal to its tangent at the wall if pumped into the tube rheometer. As a direct consequence of this, the term denoted by $8v/D$ is referred to as the pseudo shear rate, and the function in question is called the pseudo shear curve. The tested fluid is considered to be Bingham plastic if the pseudo shear curve is in the form of a straight line, but the origin does not serve as the starting point. Non-Newtonian tube rheometer tests are challenging to evaluate; they require an accurate rheological model, and then a specific evaluation protocol for a specific non-Newtonian model (Faitli et al., 2017).

2.5.3 Cylinder – Cylinder Rotational Rheometers

Having an in-depth understanding of the equipment operation to be used in the determination of the rheological properties of the FLM mixture is critical for effective application and accuracy of results attained. In this case, cylinder-cylinder rotational rheometer was applied. A rheometer is a device applied to determine behaviour of liquid, slurry or suspension when a force is applied (Yousefi, 2001). A rheometer determines both thickness and viscoelasticity of solids, liquids, and semi-solids. Viscosity is defined as the substance resistance to distortion and it operates the role

of rating shear rate or shear stress, with time and temperature dependency. On the other hand, viscoelasticity is defined as the property defining a material that illustrates both viscid and flexible behaviour. A rheometer can be used with different geometries such as cone and plate, parallel plate, torsion rectangular and concentric cylinders. However, for this study, cylinder-cylinder rotational rheometer cylinders were applied, thus makes the centre of discussion. Cylinder – cylinder rheometer has inner cylinder (bob) and an outer cylinder (crucible). The bob rotates while the cup is left stationary (see Figure 9). The rotational rheometer can be used to determine the viscosity of both Newtonian and Non-Newtonian fluids compared to falling sphere viscometer, thus making it a better choice for the study.

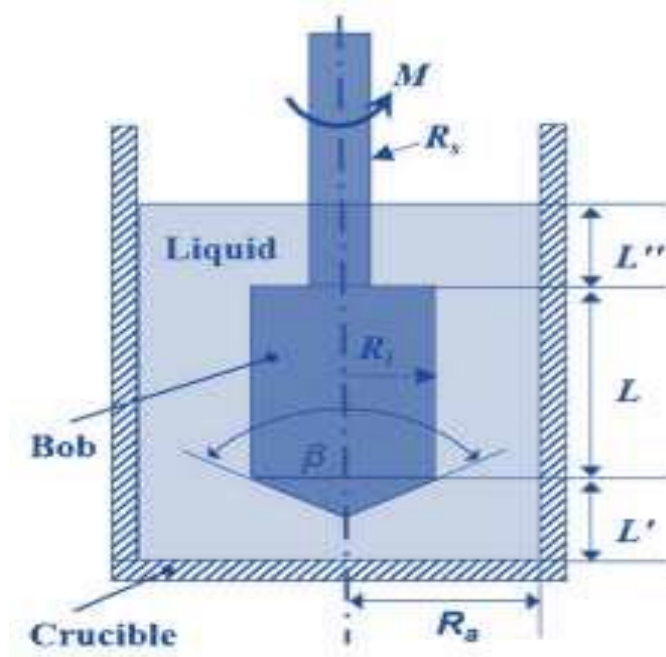


Figure 9 Cylinder – cylinder geometric system (Yousefi, 2001)

A rotational rheometer applies or measures the torque (force), angular displacement and angular velocity (see Figure 10).

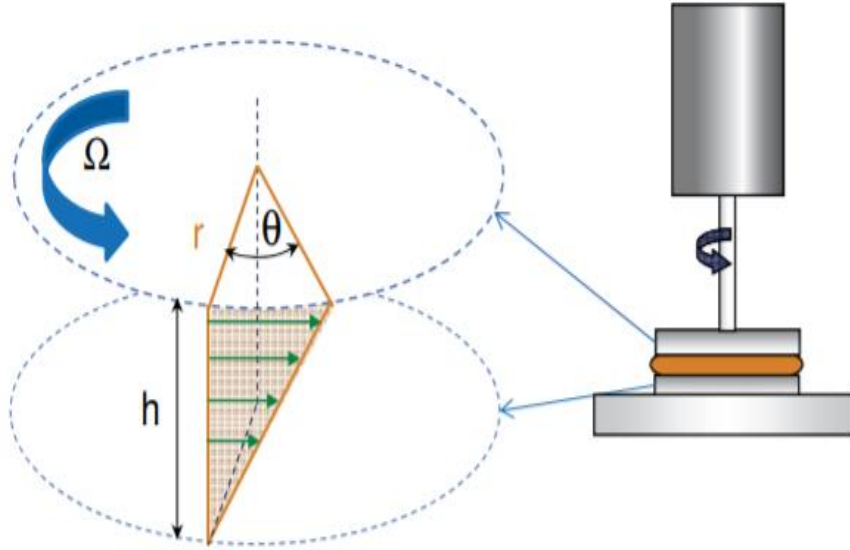


Figure 10 Working principle and the parameters of the rotational rheometer used in determining viscosity of a fluid (Yousefi, 2001)

In a rheometer, the stress is determined from the torque given by the formula

$$\sigma = M \cdot K_{\sigma} \quad (12)$$

Where σ = Stress (Pa or Dyne/cm²)

M = torque in Nm or gm cm

K_{σ} = Stress constant

The stress constant K_{σ} , is a geometry dependent factor

Angular displacement yields the shear strain, given by the formula

$$\gamma = K_{\gamma} \cdot \theta \quad (13)$$

Where γ = Strain

K_{γ} = Strain Constant

θ = Angular motor deflection (radians)

In determining the effective equations in the conversion of machine parameters such as torque, angular displacement and angular velocity to rheological parameters, the equation of motion and other relations are commonly used.

The angular speed is directly controlled by the motor, hence shear rate given by the formula:

$$\dot{\gamma} = K_{\gamma} \cdot \Omega \quad (14)$$

Where $\dot{\gamma}$ = Shear rate

K_{γ} = Strain constant

Ω = Motor angular velocity rad/sec

Viscosity is calculated from the equation

$$\eta = \frac{\sigma}{\dot{\gamma}} = \frac{M}{\Omega} \cdot \frac{K_{\sigma}}{K_{\gamma}} \quad (15)$$

The diagram illustrates the calculation of viscosity (η) from torque (M) and angular velocity (Ω) using constitutive and geometric constants. The equation is presented as $\eta = \frac{\sigma}{\dot{\gamma}} = \frac{M}{\Omega} \cdot \frac{K_{\sigma}}{K_{\gamma}}$. Annotations include: 'Rheological Parameter' for η , 'Constitutive Equation' for the fraction $\frac{\sigma}{\dot{\gamma}}$, 'Raw rheometer Specifications' for the fraction $\frac{M}{\Omega}$, and 'Geometric Shape Constants' for the fraction $\frac{K_{\sigma}}{K_{\gamma}}$. Above the equation, 'In Spec' is above M and 'Describe Correctly' is above K_{σ} .

CHAPTER 3: MATERIALS AND METHOD

3.1 Materials

Materials used for the test included fly ash, mine water and additives (CaO and carbide lime). Mine water samples for the test were collected from the sulphide mine site, and the fly ash from Mátra Power Plant tailing ponds using sample point method. The fly ash samples were labelled based on the point of sampling and duration of their maturity. For the 30-day-old fly ash samples, they were in bags marked A₁ and A₂. For half-a-year-old fly ash samples, they were placed in bags marked A₃ -A₆. Fly ashes of one year old were marked in bags A₇ – A₁₀. For two-year-old fly ashes, they were in bags M₂ – M₆. Finally, the four-year-old fly ash samples were placed in bags M₁₄ – M₁₈. Table 1 summarizes the fly ash and mine water samples collected for the study as well as the additives. Mine water was collected in several 20-litre jerricans. The limes were contained in separate bags named CaO and KM (carbide lime).

For the tests, the fly ash samples based on the maturity were measured in equal proportion and thoroughly mixed to form a uniform sample for the specified maturity period. For example, 30-day-old fly ash used in the rheological tests was measure from sample marked A₁ and A₂ in equal proportion and the two mixed thoroughly before being subjected to further tests. This was to ensure homogenisation of the samples of the same maturity and to warrant test accuracy by ensuring a representative sample. A similar procedure was done for other fly ash groups.

Table 2 Samples of materials used in the study (Author)

Fly ash samples			Additives	Mine water
Maturity	Days/months	Code used	CaO and KM	20 litre jerricans
30	Days	P30N		
6	Months	P05E		
12	Months	P1E		
24	Months	P2E		
48	Months	P4E		

In the context of the aforementioned study, the Institute of Raw Material Preparation and Environmental Protection carried out analyses on the physical characteristics of the materials that were put to use (Institute of Raw Material Preparation and Environmental Processing, 2021). I used data on the particle size distribution, particle density, and moisture content to calculate the necessary masses of materials for mixing a given recipe for backfilling mixture.

Table 3 The total moisture content and particle density of fly-ash, quicklime and carbide lime samples (Institute of Raw Material Preparation and Environmental Processing, 2021)

	P30N	P05E	P1E	P2E	P4E	CaO	KM
Total moisture content [% m/m]	38.5	46.5	45.6	35.0	33.7	0.0	57.8
Particle density [g/cm ³]	2.033	2.102	2.106	2.121	2.109	3.133	2.218

The Rosin-Rammler function was curve fitted on the measured points of the empirical particle size – distribution curves (see figure 11).

$$F_n(X) = 1 - \exp \left\{ -\ln 2 \cdot \left(\frac{X}{X_{50}} \right)^m \right\} \quad (16)$$

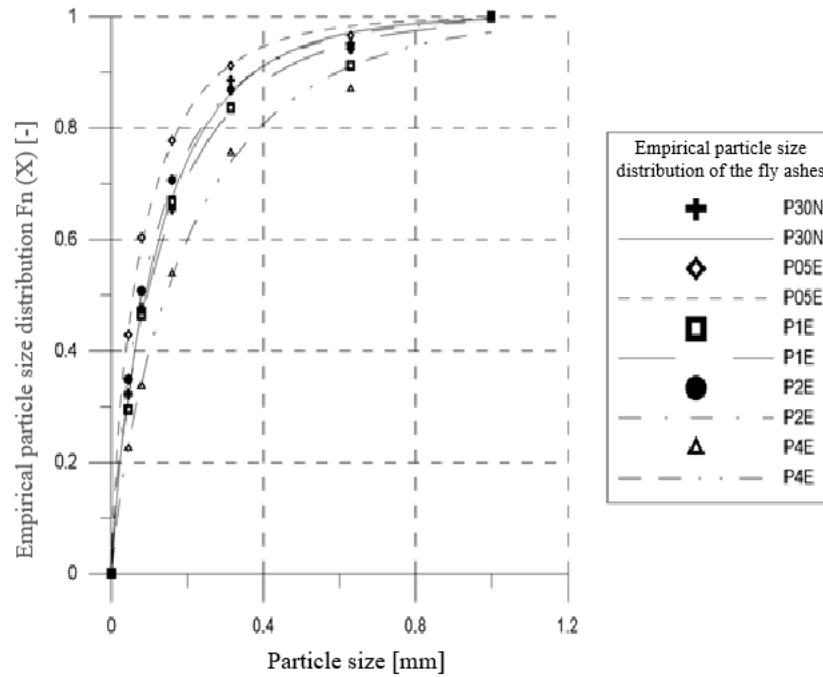


Figure 11 Particle size distribution analysis curve (Institute of Raw Material Preparation and Environmental Processing, 2021).

Table 4 Notable particle sizes of the fly-ash samples (Institute of Raw Material Preparation and Environmental Processing, 2021)

Fly-ash	X_{20} [μm]	X_{50} [μm]	X_{80} [μm]	m [-] Rosin-Rammler exponent	R^2 Coefficient of determination
P30N	23	90	250	0.83	0.998
P05E	14	57	180	0.74	0.999
P1E	23	95	280	0.79	0.996
P2E	18	79	240	0.77	0.999
P4E	37	142	390	0.84	0.996

In this research 40 different backfilling mixture recipes were used, therefore, a symbol system was developed. An example is shown:

P2EKM3C35

In the above symbol system used, P represent the fly ash, E represents the year (hence 2E means 2-year-old), KM3 represents the additive used and its mass ratio (3%), C35 represent the volumetric concentration of solid phase (35%). Equation 17 and 18 show how the mass ratio and volumetric concentration were calculated.

$$\text{mass ratio of additive: } \varepsilon_m = \frac{\text{dry mass of additive}}{\text{dry mass of fly-ash}} \quad (17)$$

$$\text{volumetric concentration of solid phase: } C_V = \frac{\text{volume of solid phase}}{\text{volume of mixture}} \quad (18)$$

3.2 Methods

In order to understand the usability of the Mátra Power Plant fly ash for the specified backfilling task, the central aim of the backfilling process was investigated. Cognisant of the critical objective, the applied technology and material properties thus have to fulfil the listed objectives, namely closing the free surface of the ore, protecting mine water from pollution, eliminating oxidation of the ore, filling mine cavities, controlling collection and treatment of infiltrating water. The primary objective of the backfilling operation is to seal the voids from the effects of air, limiting acid rock drainage. The most appropriate method to fill the cavities is to add fine grained materials onto them with the appropriate buffer potential. Fly ash proved to be a vital choice; nevertheless, water is deemed necessary for the hydraulic transportation of the fly ash into the mines. There is water potential at the site that can be applied for the hydraulic transportation, however, the pH was reported to be very low (pH 2...3), thus, its application only in small proportion is needed to eliminate possibility of secondary leaching effect and the hindered settling of the particles (Faitli et al., 2010)

3.2.1 Determining shear stress and shear rate

An Anton-Paar Physica MCR 51 type rotational rheometer (see figure 12) was applied to determine the shear stress and shear rate of the fly ash-lime-mine water mixture.



Figure 12 Anton-Paar Physica MCR 51 rotational rheometer (Author)

The fly ash, lime and mine water quantities were varied based on the already calculate amounts. An electronic weighing scale was used to measure the exact amount of the fly ash, lime, and mine water. The measured quantities were then mixed and thoroughly stirred in a rheometer cylinder cup. The rheometer cylinder cup was set into its position and the cylinder bob was set as well. The rheometer equipment was set and the revolution of the rotor powering the cylinder bob set at the highest revolution 1500 l/s and lowest at 10 1/s. Other parameters of the rotational rheometer such as temperature (25°C) and cylinder bob height (142 mm) were set from the rheometer application known as RHEOPLUS installed in a computer connected to the equipment. Fly ash of varied maturity ranging from 30 days to 4 years old were measured, with each being varied in quantity and the data recorded with Rheoplus data collection program.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Results

In this chapter, the results from the experiment were plotted and subjected to analysis. The analysis was done based on the year of maturity of the fly ash, with the initial analysis being for fly ash of 30 days old mixed with mine water and CaO as the lime.

4.1.1 Results based on the use of CaO as the additive

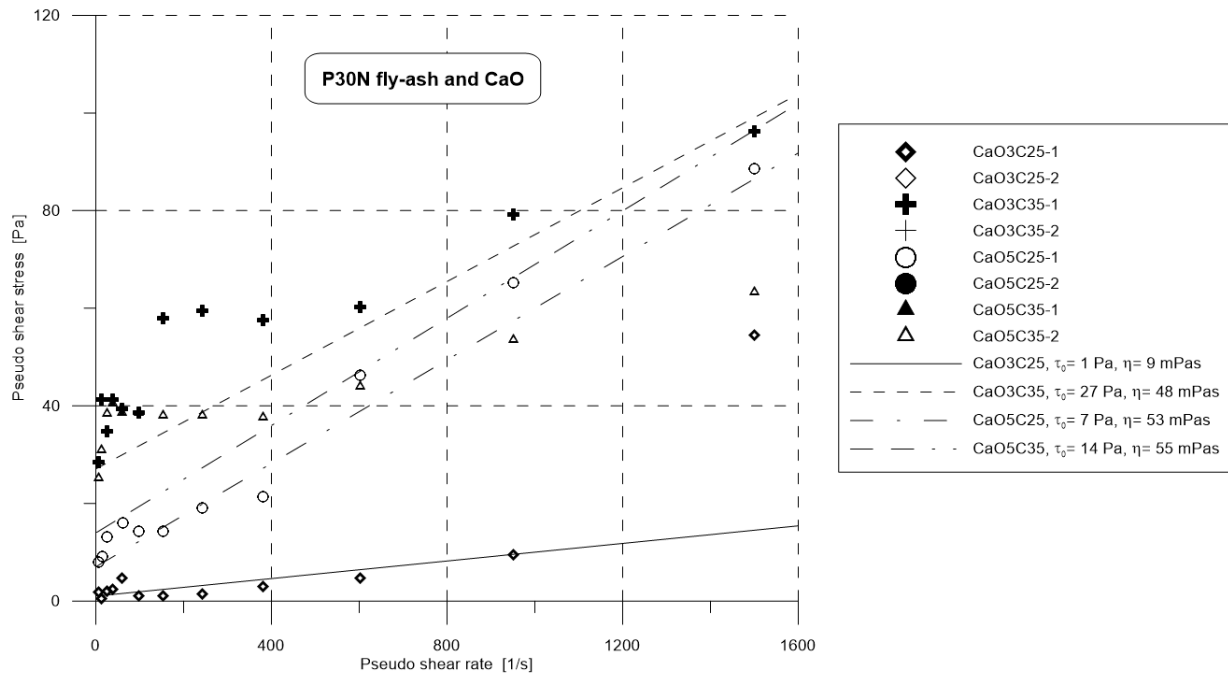


Figure 13 P30N fly ash and CaO curve representation of pseudo shear stress and pseudo shear rate (Author)

FLM mixture with the least mass ratio of the additive and highest mass ratio of the additive represented by CaO3C25 and CaO3C35 in Figure 13, showcased different rheological behaviour. However, the rheological behaviour reported is not distinct enough. This is due to the fact that increasing the mass ratio of the additive has no discernible effect on the rheological behaviour of the mixture. The yield stress and viscosity difference of the mixture are minimal at additive mass ratios of 3% and 5%. For example, when comparing CaO3C25 to CaO5C25, the minimum yield stress of the mixture is low at 1 Pa and 7 Pa respectively.

In Figure 13, the sample that has the highest volumetric concentration of the solid phase also has the highest yield stress and viscosity as observed in CaO3C35 which has 27 Pa and 48 mPas respectively. This is the case regardless of the mass ratio of the additive that is present in the sample. In figure 13, which depicts a sample of fly ash that is 30 days old, it is possible to see that the minimum pseudo yield stress of the FLM rises with an increase in the mass concentration of the volumetric concentration of the fly ash. When attempting to determine the minimum pseudo yield stress and viscosity of the FLM mixture, the solid content of the fly ash in the mixture plays a crucial role.

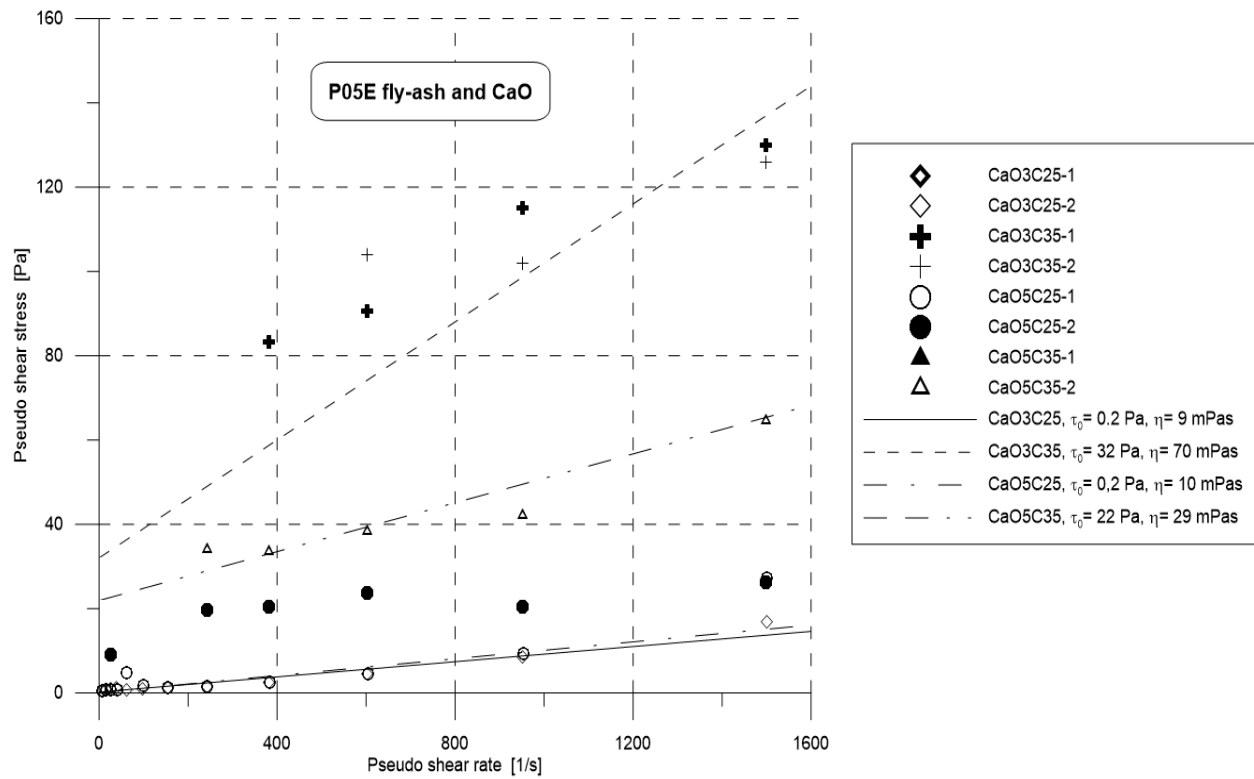


Figure 14 P05E fly ash and CaO curve representation of pseudo shear stress and pseudo shear rate (Author)

Analysis of P05E fly ash in Figure 14 showcases that CaO3C25 recorded the least minimum pseudo shear stress as well as the viscosity. The lowest minimum pseudo shear stress was also recorded by the CaO5C25 at shear stress of 0.2 Pa and viscosity of 10 mPas. However, from the graphical representation shown in Figure 14, CaO3C35 and CaO5C35 recorded the highest minimum pseudo shear stress and viscosity. From the presented analysis, it can be pointed that

irrespective of the age of the fly ash, volumetric concentration of the solid phase in the mixture plays a vital role in defining the strength of the material to be used as a backfill. This can be supported by the evidence presented in Figure 14, which shows that as the concentration of the solid phase in the mixture increases, the minimum pseudo shear stress required to overcome the yield stress increases, and the viscosity of the mixture increases as well.

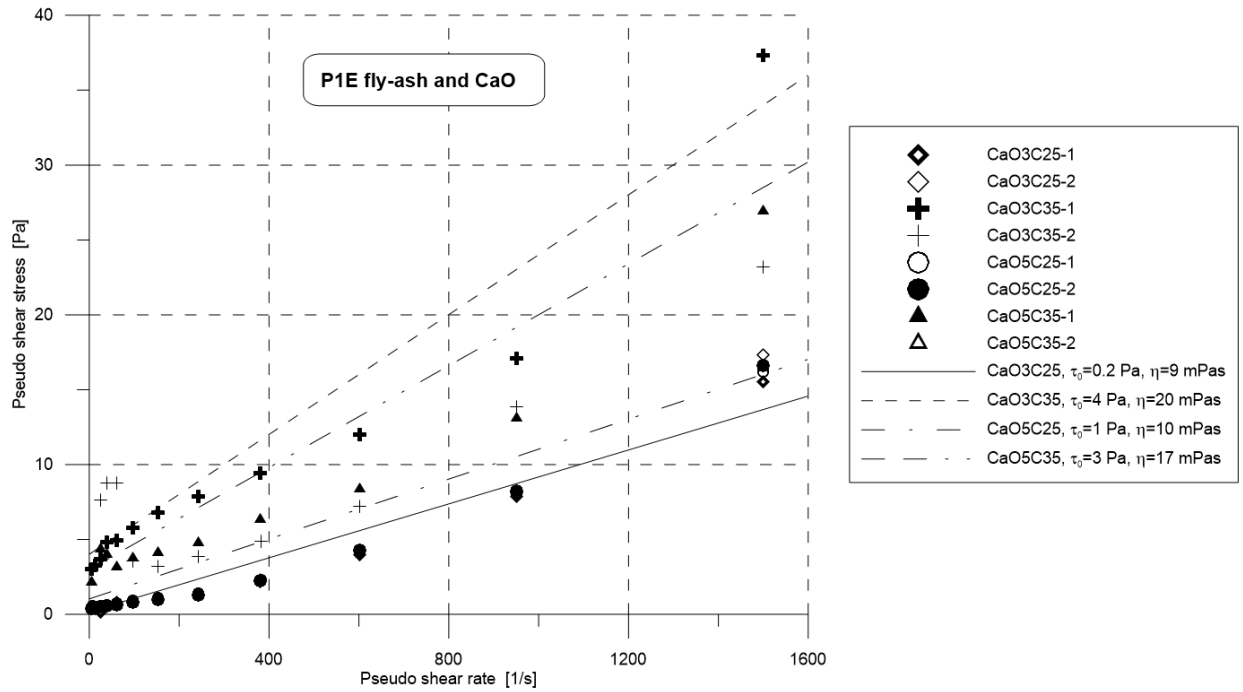


Figure 15 P1E fly ash and CaO curve representation of pseudo shear stress and pseudo shear rate
(Author)

Figure 15 depicts that mass ratio of the additive in the 1-year-old fly ash insignificantly affect the strength. This is evident in the plotted curve in Figure 15 as can be seen that CaO3C25 and CaO5C25 recorded the least minimum pseudo shear stress and viscosity. On the other hand, it can also be noted that as the volumetric concentration of the 1-year-old fly ash increases, the minimum pseudo shear stress increases as well as the viscosity of the mixture as shown by CaO3C35 and CaO5C35 samples.

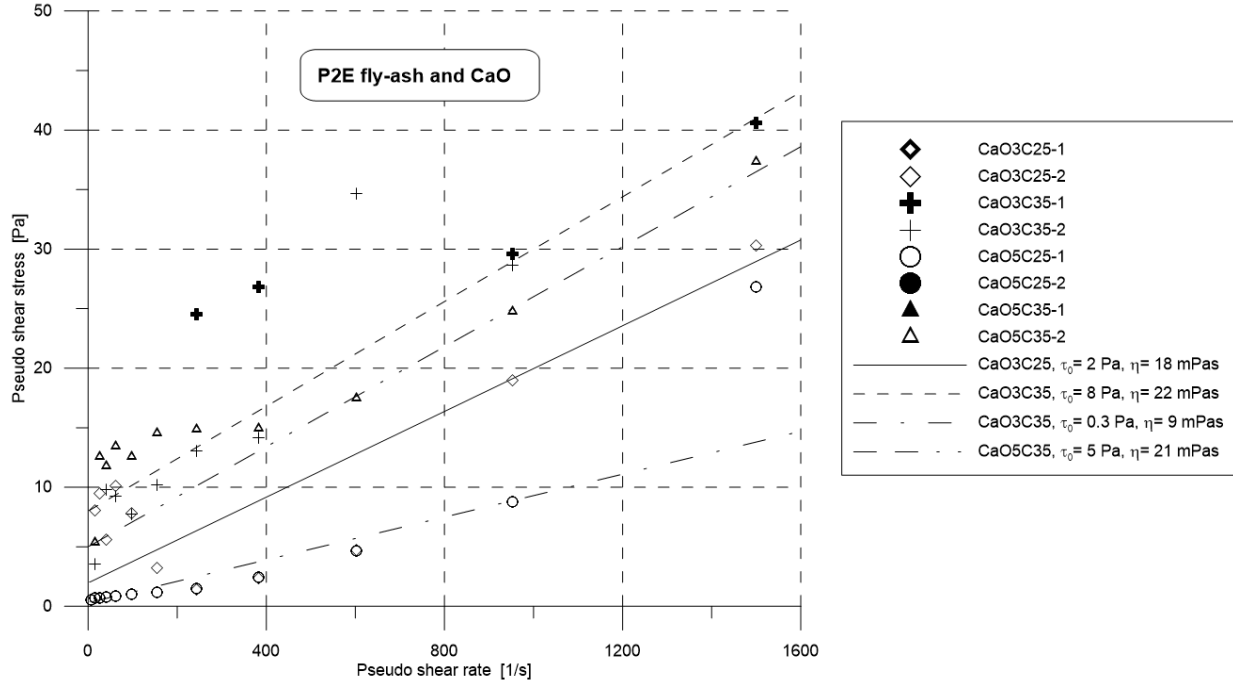


Figure 16 P2E fly ash and CaO curve representation of pseudo shear stress and pseudo shear rate
(Author)

Figure 16 is a graphical presentation of a 2-year-old fly ash -lime-mine water mixture. From the data obtained, it can be reported that the lime content in the mixture insignificantly influences the strength of the mixture. This can be observed from the data presented CaO3C25 and CaO5C25. The minimum pseudo shear stress and the viscosity of the samples are at their lowest. However, different results are obtained when the volumetric concentration of the solid phase in the mixture is increased. As the solid phase in the mixture is increased, the minimum pseudo shear stress and viscosity increases.

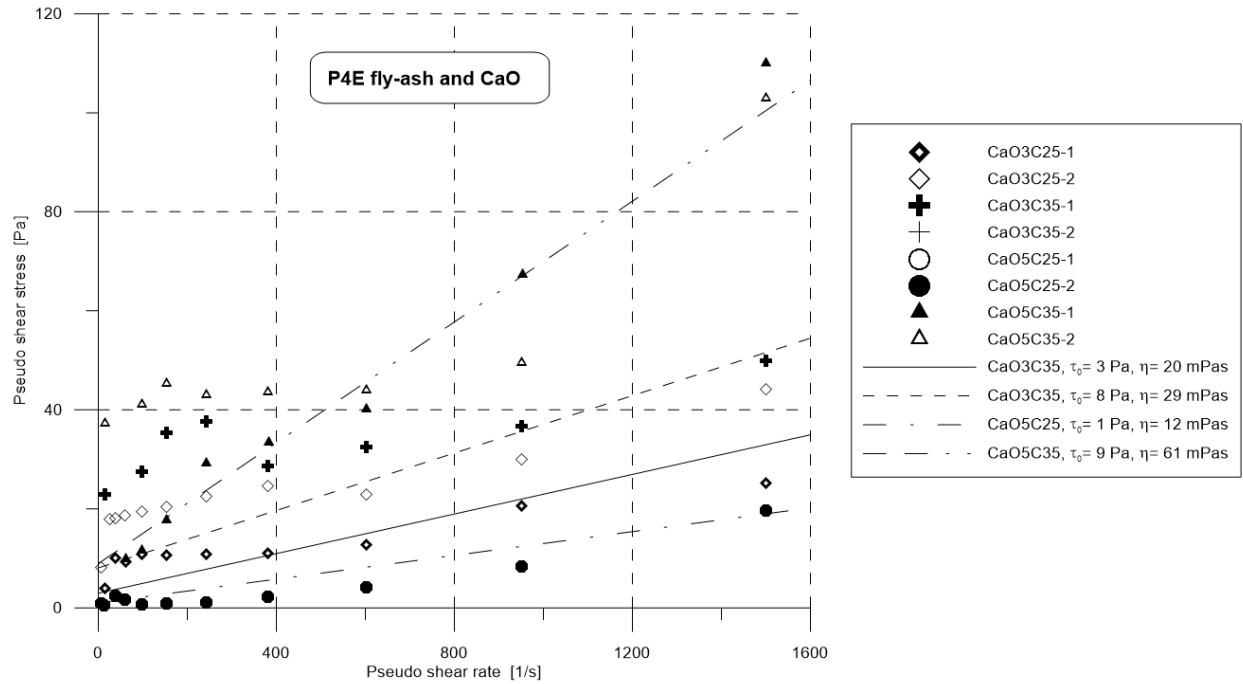


Figure 17 P4E fly ash and CaO curve representation of pseudo shear stress and pseudo shear rate
(Author)

Figure 17 is a graphical representation of the 4-year-old fly ash mixed with CaO as the additive. From the graphical data, it is evident that as the mass ratio of the additive in the mixture is increased, there is minimal impact on the overall strength of the sample. This is notable on the values of the minimum pseudo shear stress and the viscosity registered. Additionally, there is evidence of increase in the value of minimum pseudo shear stress and viscosity. This is notable as the volumetric concentration of the solid phase of the mixture is increased.

Table 5 Summary of the yield stress and plastic viscosity of the 30 days - 4-year-old fly ash with CaO used as additive

Test	Yield stress	Plastic viscosity
	[Pa]	[mPas]
P30NCaO3C25	1	9
P30NCaO3C35	27	48
P30NCaO5C25	7	53
P30NCaO5C35	14	55
P05ECaO3C25	0.2	9
P05ECaO3C35	32	70
P05ECaO5C25	0.2	10
P05ECaO5C35	22	29
P1ECaO3C25	0.2	9
P1ECaO3C35	4	20
P1ECaO5C25	1	10
P1ECaO5C35	3	17
P2ECaO3C25	2	18
P2ECaO3C25	8	22
P2ECaO3C25	0.3	9
P2ECaO3C25	5	21
P4ECaO3C25	3	20
P4ECaO3C25	8	29
P4ECaO3C25	1	12
P4ECaO3C25	9	61

Table 5 summarizes the different yield stress and plastic viscosity of all samples tested using CaO as the additive. It is important to note that during the tests, the volumetric concentration of the fly ash and mass ratio of the additive were varied for every sample.

4.1.2 Results based on the use of KM (Cabide lime) as the additive

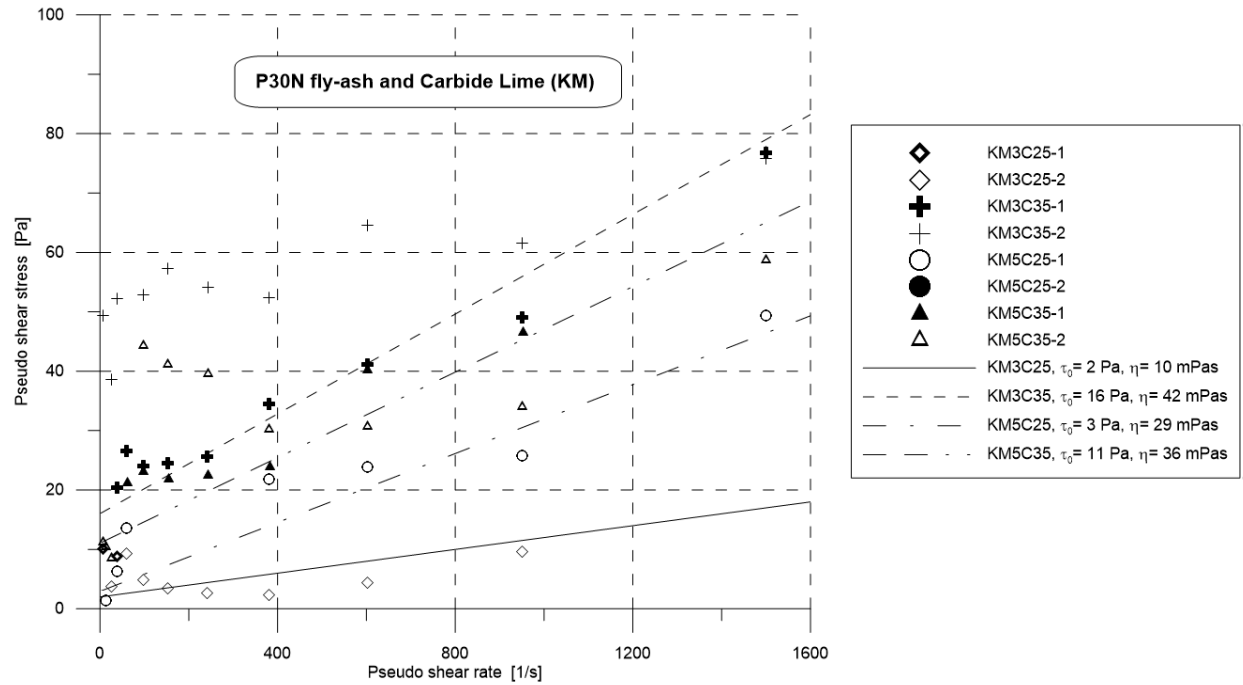


Figure 18 P30N fly ash and Carbide lime (KM) curve representation of pseudo shear stress and pseudo shear rate (Author)

The fly ash in Figure 18 has been aged for 30 days and has been mixed with KM and mine water. It should be brought to everyone's attention that the curves do not start from the origin (0,0). In addition, the inclusion of the additive KM in the mixture does not produce any discernible change in either the minimum pseudo shear stress or the viscosity of the mixture. On the other hand, elevating the volumetric concentration of the solid phase in the mixture results in an increase in both the minimum pseudo shear stress and the viscosity of the substance.

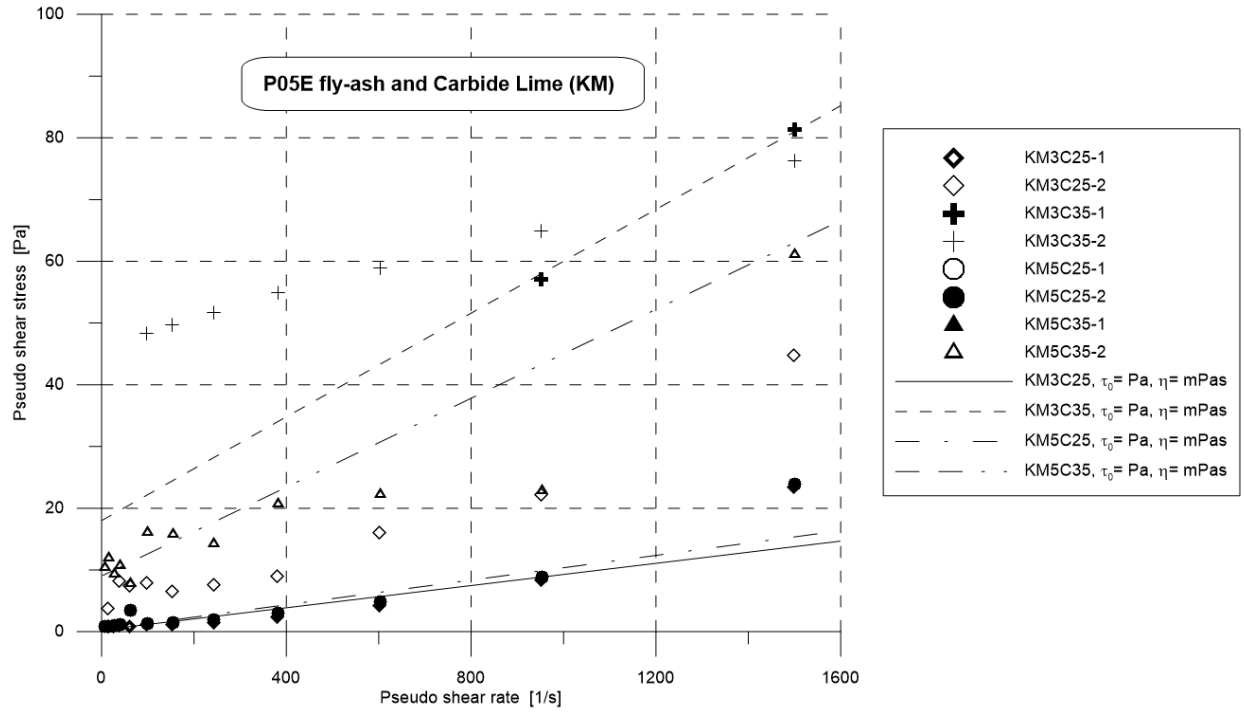


Figure 19 P0.5E fly ash and Carbide lime (KM) curve representation of pseudo shear stress and pseudo shear rate (Author)

Figure 19 is a representation of half a year-old fly ash mixed with KM and mine water. The curves do not originate from the origin (0,0). From Figure 19, it can be deduced that the additive does not affect the minimum pseudo shear stress and viscosity. This can be seen in the curve as despite the increase in the mass ratio of the additive, the minimum pseudo shear stress and the viscosity of the mixture are minimally affected, since there is minimal change. However, an increase in the solid phase by volume in the mixture constitutes a great transformation in the form of increase in the rise in minimum pseudo shear stress and the viscosity.

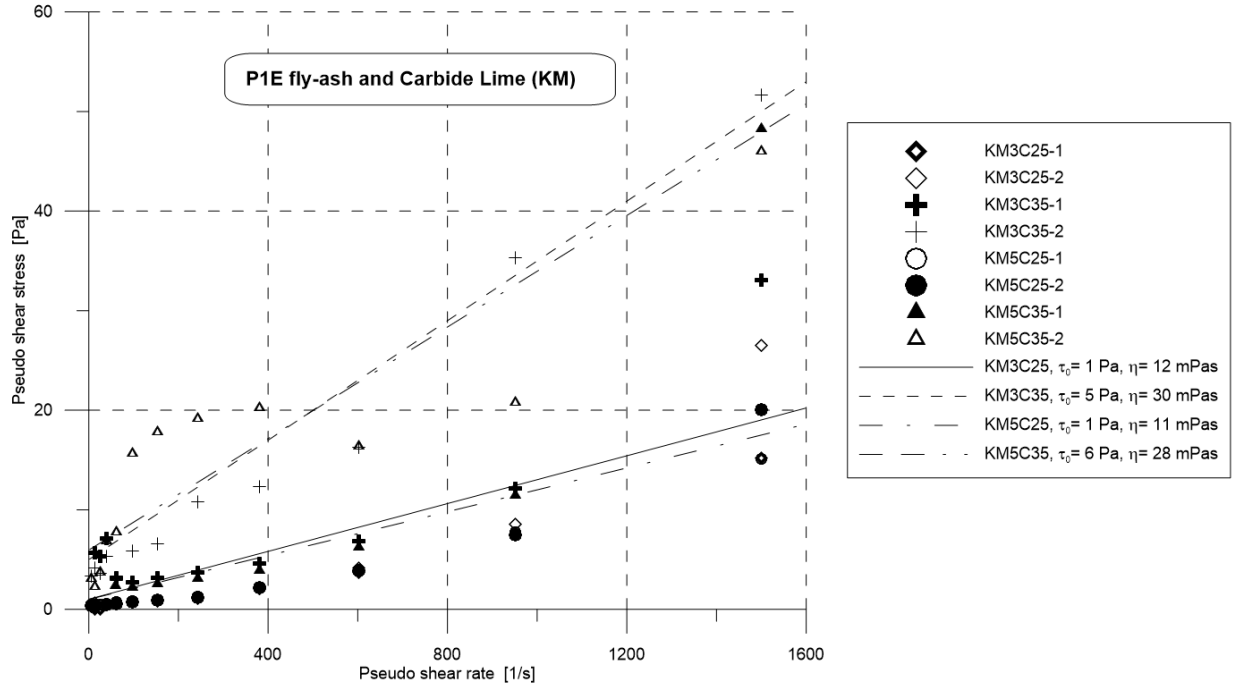


Figure 20 P1E fly ash and Carbide lime (KM) curve representation of pseudo shear stress and pseudo shear rate (Author)

The data plotted in Figure 20 represent one year-old fly ash that has been mixed with KM and mine water. The data from the curve show that the minimum pseudo shear stress and viscosity of the samples were lower when they contained a lower volumetric concentration of the solid phase in the mixture. While the volumetric concentration of the solid phase in the mixture was at its lowest, increasing the KM additive by mass did not have any effect on the shear stress or viscosity of the mixture. The samples that contained the greatest amount of KM had the least amount of shear stress and viscosity, all while keeping the same volume of solid phase in the mixture.

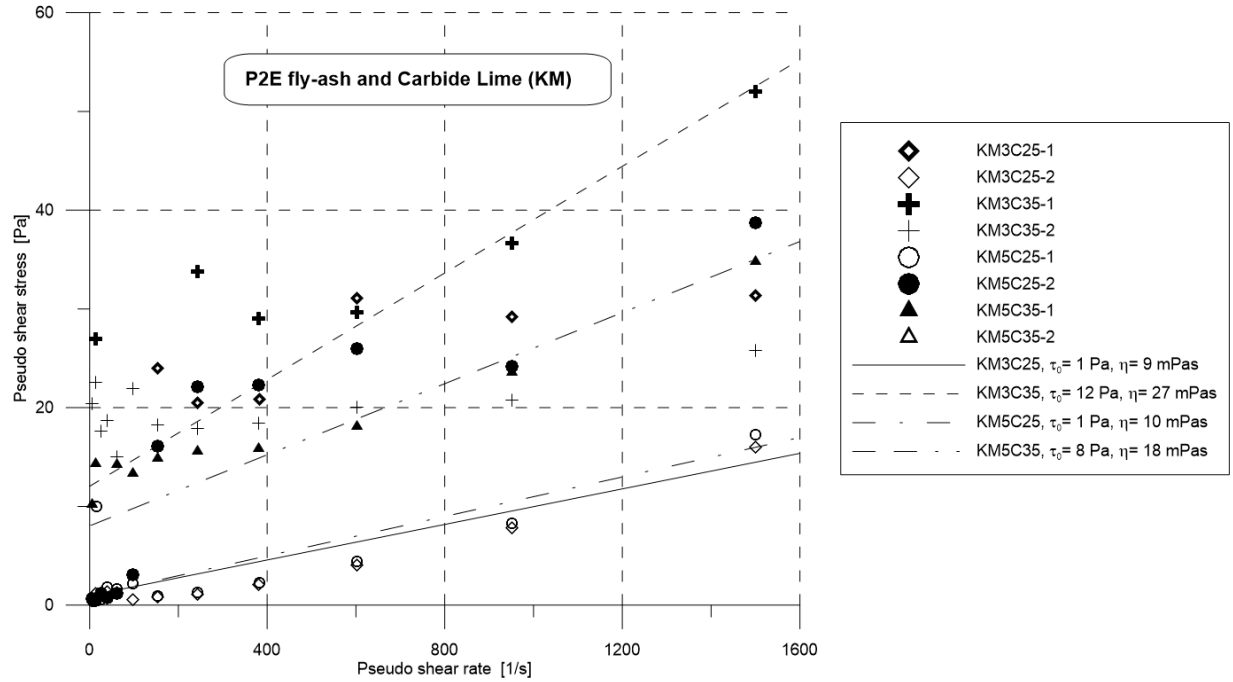


Figure 21 P2E fly ash and Carbide lime (KM) curve representation of pseudo shear stress and pseudo shear rate (Author)

Figure 21 is a graphical presentation of a 2-year-old fly ash -lime-mine water mixture. From the data obtained, it can be reported that the lime content in the mixture insignificantly influences the strength of the mixture. This can be observed from the data presented CaO325 and CaO5C25. The minimum pseudo shear stress and the viscosity of the samples are at their lowest. However, different results are obtained when the volumetric concentration of the solid phase in the mixture is increased. As the solid phase in the mixture is increased, the minimum pseudo shear stress and viscosity increases.

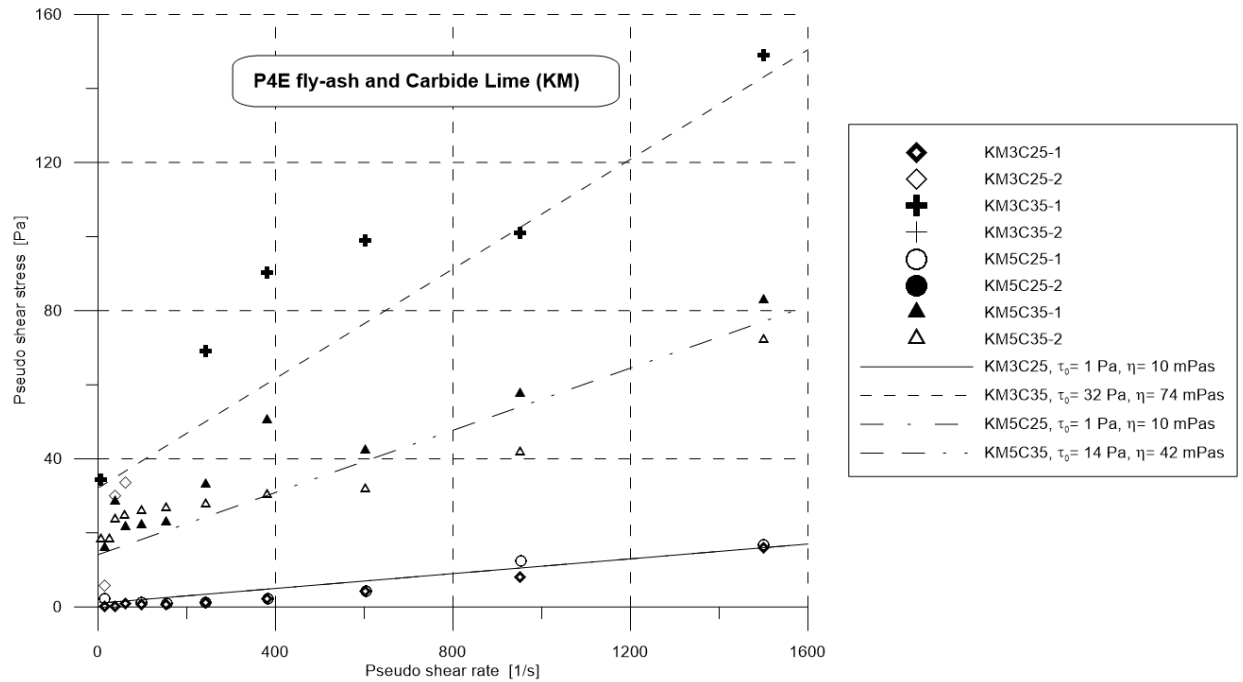


Figure 22 P4E fly ash and Carbide lime (KM) curve representation of pseudo shear stress and pseudo shear rate (Author)

Figure 22 is a graphical representation of the 4-year-old fly ash mixed with KM as the additive. From the graphical data, it is evident that as the mass ratio of the additive in the mixture is increased, there is minimal impact on the overall strength of the sample. This is notable on the values of the minimum pseudo shear stress and the viscosity registered. Additionally, there is evidence of increase in the value of minimum pseudo shear stress and viscosity. This is notable as the volumetric concentration of the solid phase of the mixture is increased.

Table 6 Summary of the yield stress and plastic viscosity of the 30 days - 4-year-old fly ash with KM used as additive

Test	Yield stress	Plastic viscosity
	[Pa]	[mPas]
P30NKM3C25	2	10
P30NKM3C35	16	42
P30NKM5C25	3	29
P30NKM5C35	11	36
P05EKM3C25	0.3	9
P05EKM3C35	18	42
P05EKM5C25	0.3	10
P05EKM5C35	9	36
P1EKM3C25	1	12
P1EKM3C35	5	30
P1EKM5C25	1	11
P1EKM5C35	6	28
P2EKM3C25	1	9
P2EKM3C25	12	27
P2EKM3C25	1	10
P2EKM3C25	8	18
P4EKM3C25	1	10
P4EKM3C25	32	74
P4EKM3C25	1	10
P4EKM3C25	14	42

Table 6 summarizes the different yield stress and plastic viscosity of all samples tested using KM as the additive. It is important to note that during the tests, the volumetric concentration of the fly ash and mass ratio of the additive were varied for every sample.

4.2 Discussion

In this section, the summary in Table 5 and 6 will be subjected to in-depth analysis and discussion with the intent of showcasing the observations made in the results section.

The curves Figure 13 to Figure 22 showcased a near similar trend. They all never started from the origin. This showcase that the mixture is not Newtonian. The data presented had minimum pseudo shear stress, which is a characteristic of a Bingham plastic fluids.

Taking reference to Table 5 and 6 that summarizes the entire data for the fly ash from 30 days to 4 years, and CaO and KM used as an additive, it can be pointed that additives in the mixture played insignificant role in the FLM mixture. This is noted by the fact that despite an increase in the mass ratio of the additive, the strength of the mixture did not improve significantly. This is supported by the fact that the minimum pseudo shear stress required to overcome the mixture's minimum shear stress point was low when compared to using the same amount of additive but increasing the volumetric concentration of the solid phase in the mixture. This finding demonstrates that the volumetric concentration of the solid phase in the mixture has a significant impact on the minimum pseudo shear stress required to overcome the mixture's minimum shear stress. According to Qi et al. (2015), the pozzolanic properties of fly ash make it the material of choice for use in backfill, hence the notable insignificant changes when different additives are applied. The fly ash, when left to sit for an extended period of time in the presence of calcium hydroxide at room temperature, will eventually produce cementitious properties. According to the findings, the percentage of the mixture that was composed of solids contributed positively to its overall strength. The rheological properties of ash-tailings slurry mixtures can be affected by the degree to which the fly ash has been hydrated, as well as by the packing and arrangement of the particles. The researchers Lee et al. (2017) discovered in their study that the formation of cementitious and pozzolanic gels, which form the properties of fly ash, is the cause of the increase in shear stress that occurs as a result of the properties of fly ash. When fly ash is added, the volume of water is reduced, which results in an increase in the number of direct contacts between the particles. This is an additional significant effect of the volumetric concentration of fly ash. Shear thinning behaviour is said to be more prevalent in fluids when the concentration of solid particles is increased, which was not the case for the FLM mixture that was used, as stated by Lee et al. (2017). In addition, smaller fly ash

particles are better at filling the spaces between larger ones, which makes it more difficult for the particles to slide past each other when they are being sheared.

On the other hand, FLM mixtures in which KM was used as the additive produced different results in terms of shear stress and viscosity. When compared to the FLM mixture's volume and mass, the KM mixture's shear stress and viscosity were significantly higher. This illustration demonstrates that the KM has pertinent properties that contribute to the cementous state required for backfilling and FLM stability than the CaO does.

In relation to the fly ash age, the curves nearly resembled each other. This is a clear indication that the fly ash age does not affect its properties to be used as a backfilling material.

CHAPTER 5. CONCLUSION

The shear stress – shear rate curve of the FLM mixture were measured and analysed. Therefore, based on the experimental results and analysis, the following conclusions can be made:

1. The FLM mixture exhibited Bingham plastic fluid properties.
2. The age of the fly ash does not affect its rheological properties that make it fit for use in the development of the backfilling technology. Therefore, the sulphide mine can continue to use the available fly ash even after the Mátra Power Plant is closed down.
3. The additives have insignificant effect on the rheological properties of the fly ash.
4. The shear stress of the FLM mixture increased with an increase in the volumetric concentration of the solid phase in the mixture. This could be attributed to the combined impacts of the increased structural network due to the dense particle packing.

It is imperative to recognize that the findings presented in this study are valid for the particular fly ash used. Other samples drawn from different mines containing different minerals could present distinct rheological properties. Further studies need to be undertaken to offer more in-depth conception of these characteristics

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