ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

EFFECT OF VIBRATION ON BULK STRENGTH

M.Sc. THESIS

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Department of Mineral Processing Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TİTREŞİMİN YIĞIN MALZEMENİN DAYANIMI ÜZERİNDEKİ ETKİSİ

YÜKSEK LİSANS TEZİ

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Kerim TÜRKDOĞAN, a M.Sc. of student of ITU Graduate School of Science Engineering and Technology student ID 505111104 successfully defended the thesis entitled **"EFFECT OF VIBRATION ON BULK SOLIDS"**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

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August 2014 Kerim Türkdoğan
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ABBREVIATIONS

δ : Effective Angle of Internal Friction
ϕ_w : Kinematic angle of Friction
ϕ_t : Static angle of internal friction for plane or core flow bins
E.Y.L : Effective yield locus
I.Y.L : Instantaneous yield locus
kPa : Kilopascal
Ps : Preshear force (Newton)
PsL : Preshear load
s : Second
S : Shear force
S^{norm} : Normalized shear force (Newton)
$S^{norm(kPa)}$: Normalized shear stress in units of Pascal
SL : Shear load
V : Normal force
W.Y.L : Wall yield locus

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EFFECT OF VIBRATION ON BULK STRENGTH

SUMMARY

Bulk material handling facilities are commonly used in many industries such as mainly in mineral processing, mining and also chemical, construction, and agriculture.

The bulk material handling facilities such as silos, stockpiles, belt conveyors should be designed specific to material that to be handled and process. The conceptual engineering of bulk material facilities has been disregarded thus lots of problems mainly blockages are generally observed. These problems are so common that; the engineers on the fields cannot believe a silo can be designed without blockages: it is kind of a learned helplessness. Beside all, the blockages in silo cause very risky situations for the safety of employees. It is challenging job to remove a blockage in a silo: Workers usually go to top of the blockage, and drilling the surface that they are standing. It is very risk. In the past some deathful accident was recorded in Turkey. Also workers sometimes try to remove blockage from the outlet of the silo by trying to penetrate into bulk with some sticks. It is an also highly dangerous method and some highly injured accidents were recorded also. Nowadays, it is possible to design a non-blocked silo with correct sampling in our country.

The conceptual design of silos is based on the results of Jenike type direct shear tester. The shear test simulates the flow of material under pressure and presents results how material flows internally and how it flows while interacting with a wall liner. For the best results the environmental affects, temperature, vibration, and process conditions are simulated.

On the other hand, with existing silos instead of re-designing and building it some external flow promoters are used. For example: air blasters and vibrations. Even though those solutions are temporary, they are commonly used because of the concern in the cost manner.

In order to obtain a successful design all the environmental factor should successfully be simulated. Vibration is commonly felt in industrial areas such as mining sites and plants. The vibration has usually low frequency and it increase the consolidation of the material in the silo. The simulation of the effect of the vibration in laboratory is supplied by resting the samples under pressure and vibration till they reach the maximum consolidation. The shear tests were made by the samples so that the effect of vibration on the storage - but not on the flow- of bulk material is measured.

Vibration is both flow promoter and flow preventer. Therefore in order to use vibration as flow promoter, the parameters of vibration that actually promotes flow should be figured out.

In this thesis, an experimental setup designed to measure the effect of the vibration on the flow of bulk solids in order to figure out the parameters to use vibration as flow promoter. The experimental setup is a modified Jenike type shear tester with vibrational equipment and firstly developed by Prof. Roberts in 1981. In the experiments the vibration is applied during shear part and the effect of vibration onto flow of the material is investigated.

In conclusion of the experiments and data analysis, with the increase of vibrational velocity lower shear stresses were observed.

TİTREŞİMİN YIĞIN MALZEMENİN DAYANIMI ÜZERİNDEKİ ETKİSİ

ÖZET

Yığın malzeme depolama sistemleri yani silolar cevher hazırlama ve madencilik başta olmak üzere kimyasal, gıda, inşaat, tarım gibi birçok alanda kullanılmaktadır.

Silo, stok sahası ve transfer şutları, konveyörler gibi diğer yığın malzeme taşıma sistemleri malzemeye ve prosese özel olarak tasarlanmalıdır. Türkiye'de şimdiye kadar ihmal edilen temel mühendislik çalışmalarından dolayı silolarda tıkanmalar başta olmak üzere çeşitli sorunlar yaygın olarak gözükmektedir. Bu tıkanmalar o kadar yaygındır ki; sektördeki mühendisler tıkanmayan bir silonun tasarlanabileceğin inanmakta zorlanmaktadırlar. Başka bir deyişle silo tıkanmaları öğrenilmiş çaresizlik haline gelmiştir. Siloların tıkanması iş güvenliğini de yüksek ölçüde tehlikeye atmaktadır. Tıkalı bir siloyu açmak için işçilerin silonun üstünden grip altlarındaki birikmiş kısmı kazarken malzemenin hareketi sonucu işçilerin ölmesi; keza silonun altından tıkanıklığı açmayan çalışan işçilerin üzerine malzeme dökülmesi sonucu ağır yaralanmaları daha önce ülkemizde yaşanmıştır. Bugün, ülkemizde doğru bir örnekleme yapıldığı takdirde tıkanmayan bir silo tasarlamak mümkündür.

Silo tasarımı sırasında Jenike tipi direkt kesme gerilimi deneyleri ile malzemenin çeşitli basınçlar altında kendi içindeki ve bir duvar astarıyla temas halindeki hareketinin/akışının bir profili ortaya çıkartılır. Bu deneyler sırasında çevresel etmenler (sıcaklık, titreşim) ve proses koşulları simule edilir.

Mevcut tıkanmış silolarda akışı geliştirmek için patlaç, titreşim motorları gibi çeşitli dış ekipmanlar kullanılmaktadır. Bunlar çoğunlukla kalıcı bir çözüm yerine kısa süreli geçici çözümler sağlamaktadır lakin endüstri tarafından sıkça tercih edilmektedir. Bunun sebebi yatırımcıların daha ucuz çözümlere yönelmesidir.

Yığın malzeme kesme gerilmeleri deneyinde başarılı bir silo tasarlayabilmek için çevresel etmenler başarıyla simule edilmelidir. Fabrika, maden sahaları gibi endüstriyel alanlarda titreşim oldukça yaygın olarak gözükmektedir. Bu titreşim

genelde düşük frekanslı olup malzemenin depolama sırasında daha çok sıkışmasına yol açmaktadır. Depolama sırasındaki bu titreşimi laboratuvar ortamında simule etmek için örnekler basınç ve titreşim altında maksimum sıkışmaya erişene kadar bekletilir ve akış özellikleri deneyleri o malzeme ile yapılır. Bu yapılan çalışma titreşimin malzemenin depolanması sırasındaki etkisini göstermek de olup; akış sırasındaki etkisini göstermemektedir.

Titreşim hem akışı zorlaştırıcı hem de akışı kolaylaştırıcı bir faktördür. Bu yüzden de titreşim bir akış kolaylaştırma faktörü olarak kullanılacaksa bu titreşimin parametrelerinin ne olması gerektiği bulunmalıdır.

Bu tez kapsamında, titreşimin hangi koşullarda uygulandığında malzeme akışını kolaylaştırabileceğini ortaya koymak için; titreşimin yığın malzemenin dayanımı üzerindeki etkisini araştıracak literatüre dayalı bir test düzeneği oluşturulmuştur. Bu test düzeneğinin ilk örneği 1981'de Prof. Roberts tarafından hazırlanmıştır. Jenike tipi direkt kesme cihazının titreşim oluşturucu ve titreşim kaydedici elemanlar ile modifiye edilmiş bir halidir. Titreşim deneye kesme sırasında uygulanarak; malzeme akışının titreşime nasıl tepki vereceği araştırılmıştır.

Tez; Giriş, Deney Düzeneği, Veri İşleme ve Deneysel Sonuçlar ve Sonuçlar olmak üzere altı ana bölümden oluşmaktadır. Giriş bölümünde yığın malzeme mühendisliğinin ortaya çıkışından ve bunun birlikte literatürde bulunan titreşimin yığın malzeme üzerindeki etkisini araştıran çalışmalardan bahsedilmektedir. Deney Düzeneği bölümünde, deney düzeneğinin oluşturulması ve deneylerin yapılması sırasında karşılaşılan problemlerden bahsedilmektedir. Bu problemler, "Deney Düzeneği Kaynaklı" ve "Malzeme Kaynaklı" olmak üzere iki başlık altında toplanmıştır. Deney Düzeneği kaynaklı problemler; titreştirici uzatma çubuğunu deney esnasında esneyerek kesme kuvvetine karşılık zıt bir kuvvet uygulaması ve genliğin uzunluk birimi cinsinden sabitlenememesidir. Malzeme Kaynaklı problemler ise; titreşimin etkisiyle aşırı yaş malzemelerdeki suyun deney düzeneğinin dışına taşması ve aşırı kuru, kohezyon kuvveti düşük, malzemelerde de malzemenin deney düzeneğinin dışına taşmasıdır.

Deneylerde öncelikle doymuş nem içeriğine sahip kömür numunesi ve kuru hematit numunesi denenmiş; ancak malzemeden kaynaklı problemler bölümünde bahsedilen sebeplerden ötürü başarılı olunamamıştır. En son %5.3 nem içerikli hematit numunesi başarılı olmuştur ve deneylerde kullanılmıştır. Numune -4,00 mm boyutunda olup iri bir dağılım göstermektedir. Deneyler 0, 25, 50, 75, 100, 150, 200 Hertz frekanslarında yapılmıştır. Deneylerde, literatürde akış fonksiyonu elde etmek için minimum gereksinim olarak belirtilen ve üç önkesme yükü ve her önkesme yükü için üç kesme yükü kullanılmıştır.

Deney sonuçlarının analizi Kesme Verisinin Analizi ve Titreşim Verisinin Analizi, şeklinde iki başlık altında incelenmiştir. Kesme Verisinin Analizi, kesme değerlerinin normalleştirilmesinden bahsetmektedir. Titreşim Verisinin Analizi ise, gürültünün titreşim verilerinden temizlenmesinden ve titreşim hızının kesme verilerini karşılaştırmak için temel parametre olarak kabul edilmesinin sebeplerinden bahsedilmektedir.

Yapılan deneyler ve data analizleri uygulanan titreşim hızının arttıkça daha düşük kesme gerilimleri elde edildiğini ortaya çıkmıştır.

1. INTRODUCTION

The first development regarding the flow properties of bulk materials were developed by Jenike Johansan who gave his name to the device “Jenike Type Direct Shear Tester” in1960’s. After that, Prof Alan Roberts modernized the works of Jenike in University of Newcastle and have honorable place in bulk material handling field. Both Jenike and Prof Roberts has taken role with setting up bulk material handling companies. Jenike & Johanson established in USA and TUNRA Bulk Solids is established in Australia.

This study took place in TUNRA Bulk Solids facilities, with the collaboration of Istanbul Technical University and The University of Newcastle.

1.1 Aim

The main aim of the study is to establish an experimental setup that can make vibrational shear test based on the development by Prof Roberts in 1980’s.

The experiments will direct us to decide what kind of vibration should use in order to obtain a flow promotion. The setup is a modified version of Jenike type shear tester.

The new set-up is based on the concept of Prof Roberts’ vibrational shear tester. It has capability to make shear and wall friction test.

1.2 General Information

Bulk material can be classified with various definitions; according to their size, type, the industry that used in. Bulk material generally means all the particulate material which sizes can differ from powder to rocks. Bulk material handling is a subject of engineering which covers all the information that needed to store and transfer bulk materials. This transportation and storage points can be in plants and also environmental. Bulk material handling commonly uses in lots of industry such as mining, construction, chemical, pharmaceutical cosmetic, agriculture. The higher particle size and capacities are usually observed in mining industry. If we have a look at to an ordinary mining operation the bulk materials handling parts can be exampled as follow: The ore-pass in underground operations, the conveying of material from underground to surface, the transfer chutes in underground also in mineral processing plant, the storage of ore after crushing in a silo or stockpile, transporting or conveying of concentrate to the port, defining transportable moisture limits, suppressing the dust when loading the dry concentrate to ship.

All of the exampled steps need the knowledge of bulk material handling. The bulk material handling knowledge basically means the knowledge of how material will behave internally and interact with a surface under different pressures. In other words the aim of bulk material handling is to supply setups that will warranty the flow of material from point A to B with the most efficient way; with minimum wear and minimum stoppage time, and capital expenditures.

Bulk materials handling is like mineral processing. In mineral processing every ore-bed has to be approached differently. Even though they have the similar type of mineralogy, all has to be processed differently. For example the process method is same for chrome ore all around Turkey: vibratory tables. However the process parameters are completely different all around the country. Bulk material handling has the same concept: no matter how much the material is similar, all different materials (i.e. same type of ore from different ore beds) has to be characterized according to their flow properties and other bulk properties.

The modern bulk material handling researches has started with the work of Jenike, Johanson et al. in 1960's. Jenike has invented a direct shear tester, "Jenike Shear Tester", which is specifically designed for bulk materials. After invention of Jenike, bulk material handling science made a big bounce. Works of Prof. Alan Robert have a very important point in the development of bulk material handling. He modernized the work of Jenike and made them more suitable for industry. Nowadays, there are two big sized bulk material handling research companies world-wide: one is Jenike & Johanson which was found by Jenike and Johanson, the other one is TUNRA Bulk Solids which was found by Prof. Alan Roberts. This information proves the importance of Jenike's and Roberts' works.

After 1980's with development of computers bulk material handling has made another bounce and modeling started integrated into bulk material handling more easily. A historical summary can be seen in Figure 1.1 (Roberts, 2013).

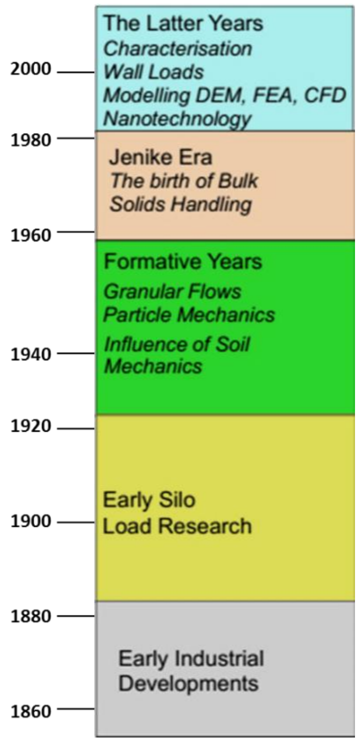


Figure 1.1: Developments in bulk material handling (Roberts, 2013).

Today with the knowledge of bulk material handling, we can design non-quaking silos, stockpile with maximum capacity, non-blocking transfer chutes with minimum wear, calculate bin wall loads, minimize segregation in different systems, dust suppression in other words: we can almost do all the engineering that can be considered in for the transportation and storage of bulk materials.

1.3 Literature

There are number of studies regarding the effect of vibration on bulk material movement on free surface. This literature survey aims to review the researches about effect of vibration on strength of bulk material which is not focused on that much in the literature. This may be a result of complexity of theoretically analysing and modelling (Roberts, 1997). Numerical modelling methods can give accurate results in free bed vibrational studies. Nevertheless, about shear strength, it has been only possible to obtain a full-empirical or semi-empirical modelling; because the knowledge of bulk strength is based on shear stress experiments.

In 1976 Crewe investigated the effect of vibration on hopper discharge. In the study, firstly, a hopper designed which causes arching under zero vibration. After that it was aimed to obtain a mass flow by applying vibration horizontally to hopper discharge chute and succeeded. Moreover it was observed that, after starting to apply vibration it takes some times to commence of flow. This delay, which is due to transmitting of vibration in soil, was almost double when pseudo random binary signals (13secs.) are used instead of sine wave vibration (7 seconds). Beside the time to empty the hopper was same because the flow rate was same for the both of the signals (Crewe 1976).

Arnold and Kaaden have investigated the effect of vibration on wall friction in 1977. In the study, they used standard Jenike method to determine wall yield loci. For vibrational conditions a horizontal vibration was applied to the plate. In results of experiments an extreme reduction in wall friction was observed (Figure 1.2.). Wall shear forces under vibrated conditions were 5 to 10% of the static results. However, because it was studied with low frequencies, in example 10 to 25 Hz. a consolidation in bulk material was also observed. As a result, writers underlined that in order to avoid consolidation, vibration should be applied along the direction of the wall. Nevertheless, such a consolidation is not observed while working with high frequencies. Moreover it was indicated hopper half angle can extremely increase with a applied vibration, in example from 9 to 40 degree, because a reduction of one degree in the effective angle of friction causes a reduction two or three degree of hopper angle (Arnold & Kaaden, 1977).

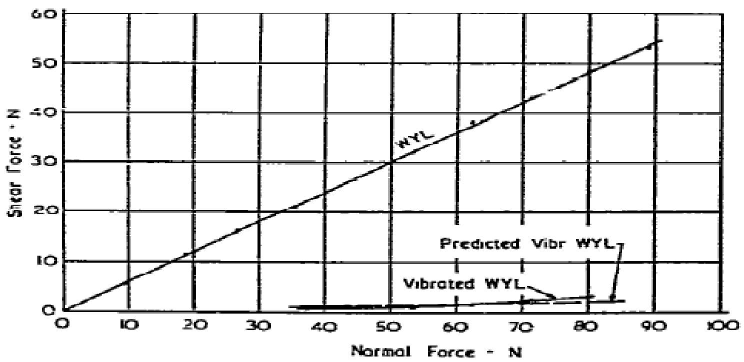


Figure 1.2: Static and vibrated wall yield loci (Arnold, Kaaden, 1977).

In 1978, K.W. Li prepare a thesis about effect of vibration on the shear strength of bulk solids in University of Newcastle. In the study a classic Jenike shear cell has improved and two different type of vibrational shear tester were designed. In first design whole cell was vibrated, in the second design only top half of the cell was vibrated. Although an oscillation was observed when the whole cell vibrated, in both situations same results were obtained. Because the top cell vibrated shear cell has an easier setup and is easier for modelling, it makes more sense to use it for further researches. In the study, a reduction in shear force and so that in the flow function was observed (Fig. 1.3). Moreover a successful mathematical model for predicting vibrated shear stress is occurred according to a physical model based on the Hvorslev's Failure Surface (Fig. 1.4) (Li, 1978).

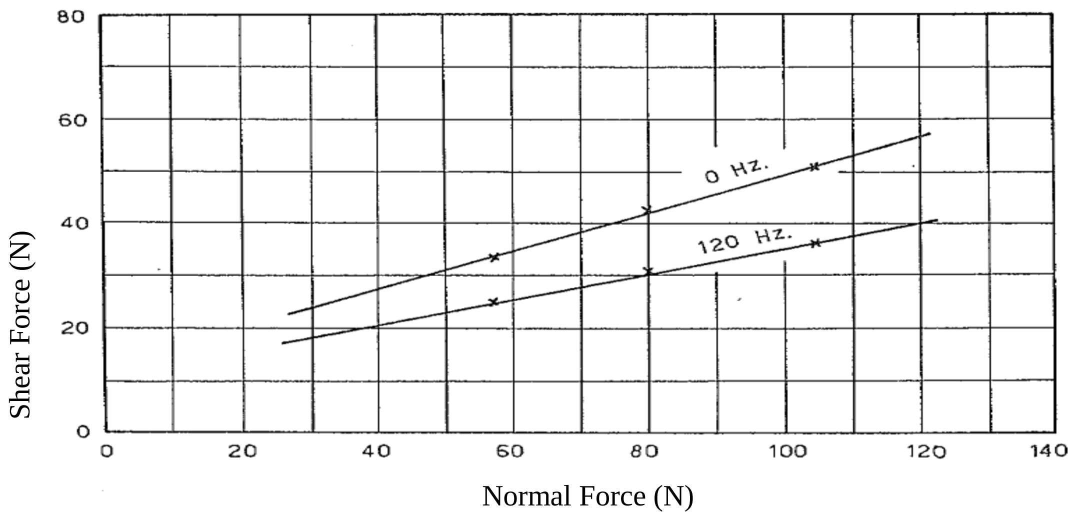


Figure 1.3: Flow function under static conditions and under vibration (Li, 1978).

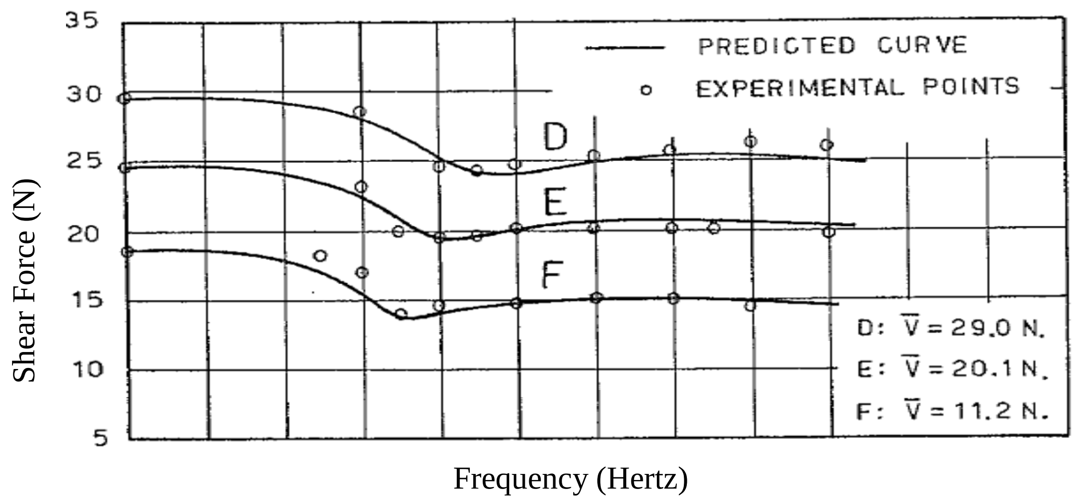


Figure 1.4: Predicted vibrated shear force curves (Li, 1978).

In 1978 Roberts and Scott published a paper on the effect of sinusoidal and random vibrations on shear strength. They got similar results to the Li's thesis. In this paper authors underlined that the reduction in shear stress is a function of frequency and doesn't matter it is sinusoid or random vibration, there is a critical frequency or combination of frequencies that reduce the shear stress to a local minimum. Moreover, a shear force vs. time graph is shared in the paper (Fig. 1.5.). It shows that, the reduction in shear strength due to vibration is not continuous. After the vibration is stopped it just increase back to same value as there is no vibration (Roberts and Scott 1978).

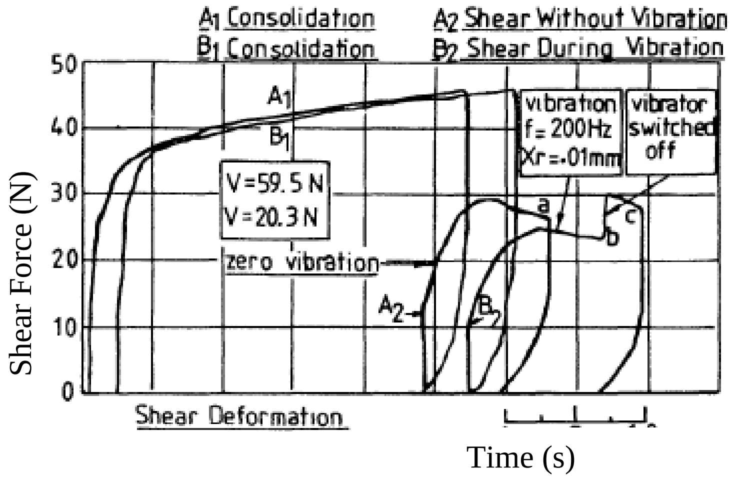


Figure 1.5: Shear stress during and after vibration (Robert, Scott 1978).

In 1978 Roberts et al. published another paper. In that study a bin with a vibrating insert was build. There is more than one frequency that makes the shear strength minimum. Therefore, it is emphasized that, even though sinusoidal are the most common one; using broad band random vibration is definitely a wiser choice as soon as the band with be wide enough to comprise critical frequencies (Roberts et al. 1978).

In 1986, Matchett A.J. occur a friction bond model for effect of sinusoidal vibration base on the concept which is defined by Matchett and Smith, of the hypothetical friction bonds acting in a shear plane (Matchett, 1986).

In 1991 Akiyama and Shimomura investigate a novel method for determining the wall shear stress of vertically vibrating particles. In this method an acrylic tube is dipped vertically to a vessel filled with granular materials. (Fig.1.6.) In the experiments, a vertical vibration with a constant frequency of 50 Hz and acceleration with 3-8 G which is adjusted by amplitude was applied vertically from bottom of vessel. After a minute vibration is started, the particle bed in the tube stays in an equilibrium position. Recording the ratio of Z_1 and Z_o, as it is seen in the figure, gives the wall shear stress by a differential equation which is defined in the paper (Akiyama & Shimomura 1991).

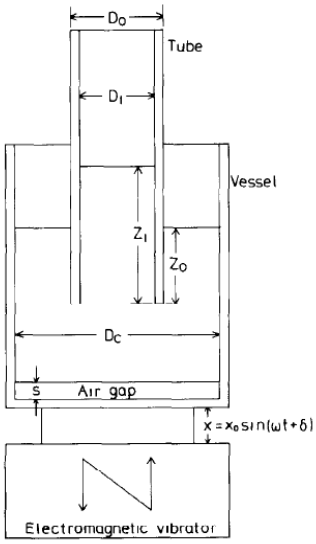


Figure 1.6: A novel method for measuring wall shear stress in vibrating particle beds (Akiyama & Shimomura 1976).

In 2000 and 2002, Kollmann and Tomas published several papers about the effect of vibration on hopper design for fine particles with average size 1 µm. They indicated that actual events in silos related with vibration can be simulated with experimental procedure as following;

Table 1.1: Procedures for vibrates shear testing (Kollman & Tomas, 2002).

Method	Vibration Excitation	Application, Examples
A[a]	during shear	pulsed vibration, e.g., for bridge breaking and discharging
B	during preshear and shear	continuous vibration during discharge, e.g., vibrating hopper
C[a]	during preconsolidation	undesirable vibration during silo filling and storage time without discharging
D	between preshear and shear	undesirable vibration during storage, e.g., transportation by truck and train (equivalent to "time consolidation")

However in the study only A and B method were used. Similar results to old studies were obtained. Moreover they emphasize that with constant frequency while amplitude of vibration is increasing the shear stress ratio which is the proportion of shear stress under vibrated conditions to under static conditions, shows an asympthote.

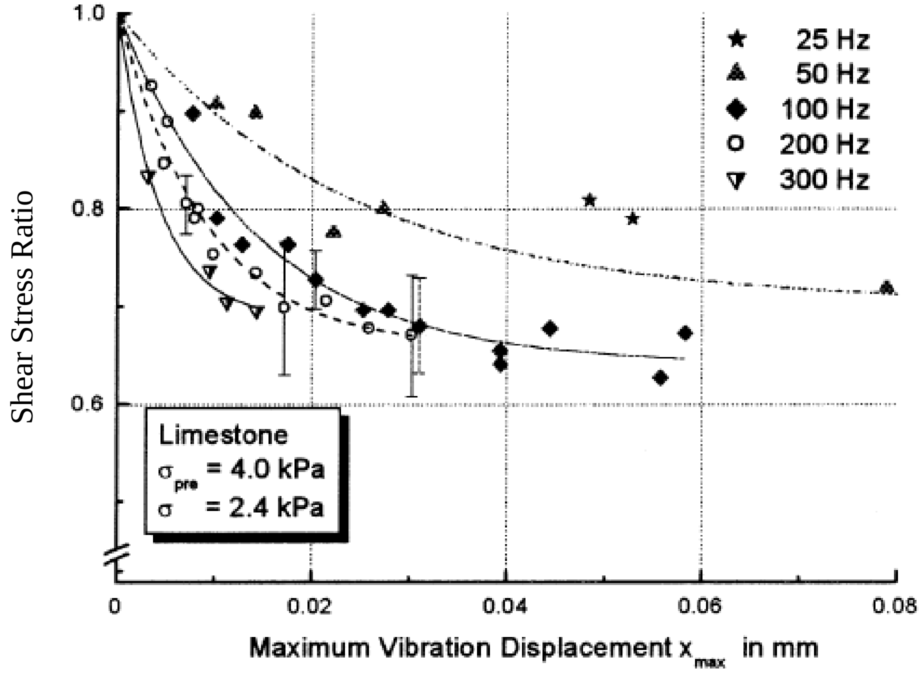


Figure 1.7: Shear stress ratio vs. amplitude (Kollman & Tomas 2002).

Also shear stress ratio versus vibration acceleration, frequency, and vibration velocity graph were plotted (Fig. 1.7, 1.8). In all graphs tendency to asymptote were observed. Highlighting that, best correlation was obtained with vibration velocity (Figure 1.8).

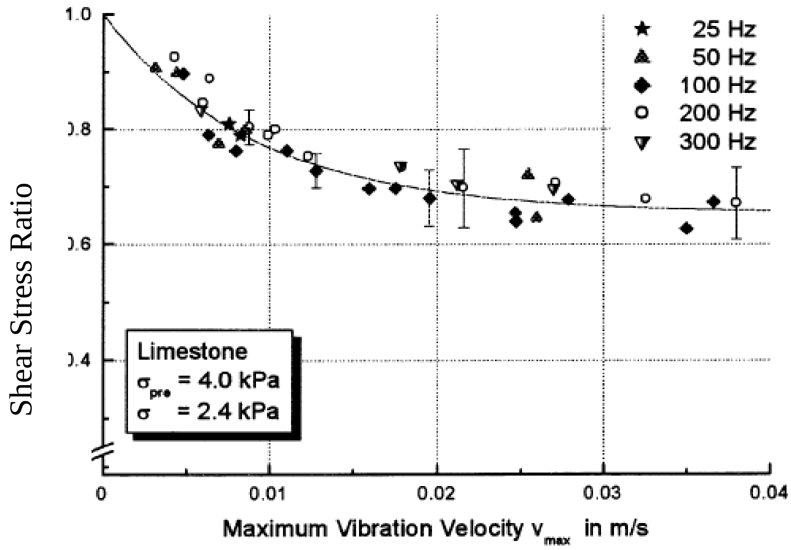


Figure 1.8: Shear stress ratio vs. vibration velocity (Kollman & Thomas 2002).

The results of the experiments which were made by applying vibration both during pre-shear (consolidation) and shear to simulate continuous vibration during discharge, gave the same results for shear stress. In other words, there is no effect of applying vibration during pre-shear on shear stress (Kollman & Thomas 2002).

1.3.1 Flow properties

The knowledge of bulk material handling starts with the flow property of material. The flow property defines how material act/flow under different pressures and interact with different surfaces. In industry bulk materials are always under pressure such as silos, stockpiles and interacting with different surfaces i.e. bin walls, transfer chutes, conveyor line, pneumatic lines. The Jenike shear test enable to determine the flow properties of material as follow:

- Effective angle of internal friction - δ
- Kinematic angle of friction (ϕ_w) between the bulk solid and sample of wall material
- Flow functions (instantaneous and time storage for different conditions of moisture, temperature
- Bulk density of material as a function of consolidation
- Extended flow functions, both instantaneous and after time storage
- Static angle of internal friction, $\phi_{t,}$ for flow or core flow bins
- Permeability to gas flow for fine dry powders

1.3.1.1 Effective angle of internal friction

The angle of friction is the angle that material will fail and slip on its surface. In other words, if some amount of bulk is put onto a surface and started to raise the surface from one point to give an inclination, the angle that material started slip on itself is the effective angle of internal friction.

1.3.1.2 Kinematic angle of friction

It is the friction angle between material and wall. If some amount of bulk is put on a wall surface and started to rise from one point to give an inclination, the angle that material started slip from the wall surface is the kinematic angel of friction.

1.3.1.3 Flow functions

The ability of flow of bulk material is defined by a function of the strength of material which is a result of consolidation (Arnold et al, 1980). In other words the relation between major consolidation force and unconfined yield force represent the flow function.

However the flowability of a bulk sample cannot be only described with consolidation pressure, there are various environmental factors which effects flowability such as moisture content, temperature, storage time. All of the factors cannot represent in a single curve thus different curves are used (Fig. 1.9., 1.10.).

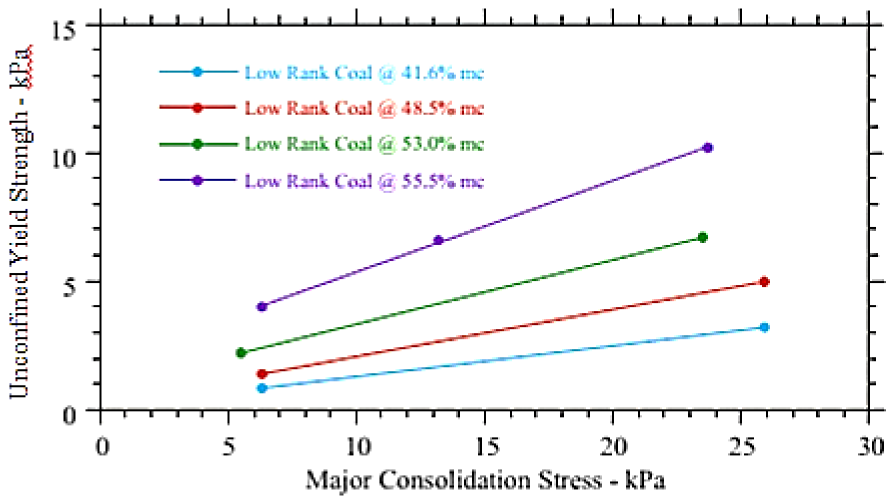


Figure 1.9: Different flow functions for different moisture contents.

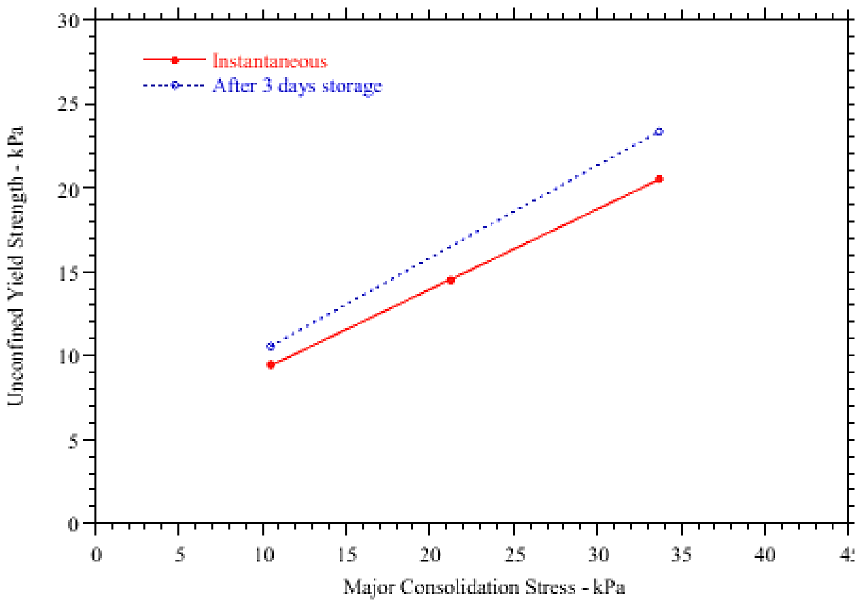


Figure 1.10: Different flow functions for different storage times.

Different storage time gives different curves also different moisture content gives different curves as well. All of those different factors should be considered before designing any bulk material handling facilities and it is strongly recommended for mining operations to take worst case condition into account so that a future problem-free plant can guaranteed.

1.3.2 Bulk density of a material as a function of consolidation

The bulk density usually separated into two groups as: Untapped and tapped bulk density. However the term "tapped" is so general, the bulk density depends how much is tapped. Therefore a compressibility test is applied in order to find out the bulk density for different major consolidation forces. The test equipment is similar with the shear tester. A cell is filled with bulk material. A lid is placed onto bulk, and different weights applied onto lid. The lid is twisted after addition of every load. The decrement in the lid for each weight is recorded and it shows the reduction in volume. In conclusion, the bulk density for different consolidation pressures are calculated with the knowledge of mass of the sample, volume of the sample and the vertical loads applied. An example of bulk density curve given in Figure 1.11 (Arnold et al.1980).

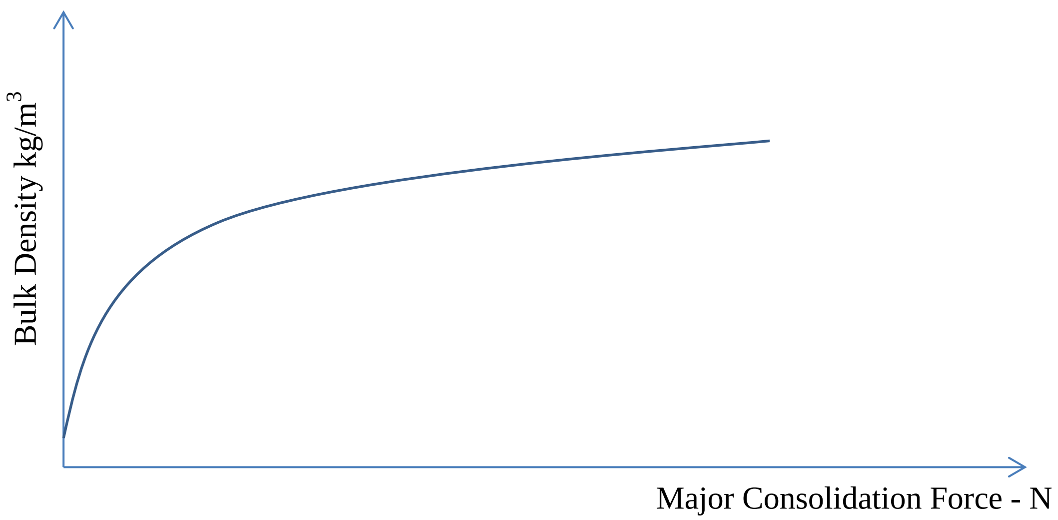


Figure 1.11: An example of bulk density curve.

1.3.3 Permeability test

"The permeability test is applied in order to be able to predict the limiting flow rate of fine powders"(Arnold et al 1980). The permeability is also like bulk density it changes with consolation stress.

1.3.4 Shear test

The aim of Jenike Type Shear Tester to measure the flow of material under different pressures which will allow an ultimate scale-up and direct engineers while designing stockpiles and silos.

Parts of the shear tester as follow: Machine part, Frame, Base, Shear cell, Shear cover, Mould Ring, Twisting Top, Carrier(0,5kg)

The basic part of the shear tester is a shear cell where actually the experiment takes place. Shear cell consist of a base, a shear ring and a cover. The shear cell has a circular structure and it’s inside diameter is either 95,3mm or 63,5 mm which makes possible to reach higher consolidation pressures during the experiment.

The mould ring and twisting top are only used during preconsolidation step which helps to form a uniform sample during experiment. A normal load is applied from the top of the cell and shear force is applied in horizontal direction. Shear force is produced by a load cell and transmitted to the shear ring by the loading stem. The shear ring slides on the base and shear the sample till the failure occurs. The loading stem has a constant strain rate so that the applied force changes during the experiment. It increases till the shear failure and suddenly drops down after. Applied force is recorded in time domain and observed simultaneously by the operator.

The machine has four operating mode as fast forward, forward, reverse and fast reverse. The fast settings are only used between runs as an ease of operation.

In other words the aim is to visualize the effect of different pressures in a bunker or silo. Therefore different normal loads are used during experiment. The normal loads are applied to the top of the cover and the shear force is applied perpendicular to normal loads’ direction. There are three different steps of the experiment: Preconsolidation, Pre - Shear and Shear

1.3.4.1 Pre- Consolidation:

Pre -consolidation is the initial step of the testing procedure. It aims to prepare an uniform sample. In this step mould ring and twisting top is replaced onto shear ring. A preconsolidation load is hanged and twisted for several times.

The load and twist number is decided according to experience. The better pre-consolidation step will give better result in consolidation step. After twisting, the mould ring is removed from its place, the remaining bulk solids on the top of the shear ring is scrapped without disturbing the material. After that the cover is replaced onto sample and ready for next step.

1.3.4.2 Pre- Shear

The consolidation step is the initial step of shear. The shear cell is started to be shear under a normal load V. When the graph of shear vs time reach a steady state position the machine is stopped and reversed until the force become zero. During the consolidation the shear ring shouldn't move further a lot, so that there will be still place for Shearing. Moreover the graph of time versus shear force determines the efficiency of pre-consolidation step. Different types of consolidation curves are seem in as "normal", "under" and "over" (Figure 1.12). The preconsolidation step should be repeated with different loads and turn numbers until a "normal" curve is obtained.

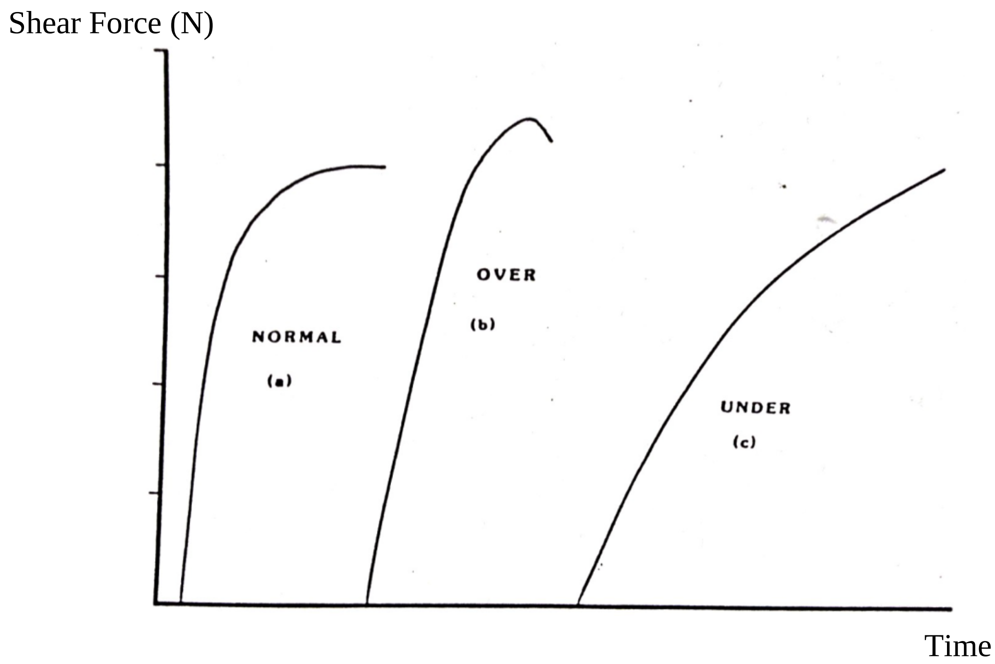


Figure 1.12:.The pre-shear results (Arnold et al. 1980).

1.3.4.3 Shearing

Shearing is the final part of the experiment. In this step, the sample is sheared under a normal load smaller than the consolidation load V_1. The pin is moved forward again. The feedback force increase makes a peek then start to decrease. The peek point means a failure plane is occurred in the sample in other words the bulk material don't hold itself anymore. This is the finalization of the experiment.

1.3.4.4 Evaluating the results of shear test

The shear test is applied according to directions above. In order to obtain a flow function number of shear test should be applied. The shear tests are conducted with different loads in order to simulate different pressures. There are two basic variable, preshear load and shear load. Under one pre-shear load three or more shear loads are chosen and experiment is done. In figure 3.1 an example to experimental logs can be seen. The first curve shows the pre-shear step and the second curve shows the shear step. The preshear load is kept constant and shear load is changed, and different S' points are obtained. Three S' point is enough to obtain yield loci (Figrue 1.13) After obtaining one yield loci the preshear load is changed and different yield locus obtained with same method. Some graphs sheets belong to this thesis project can be found in Appendix A.

The yield loci is the curve in the graph normal load (V) vs shear force (S) .The points $(V',S')_{1,2,3}$ shows the data obtained with shear and the point (V,S) shows the data obtained with preshear.(Figure 3.1.) The semi- mohr circles are drawn after the yield loci. Small semi-mohr circles should start from origin and be tangential to the yield loci. The big semi-mohr circle should be tangential to the yield loci. At least three yield locus are needed to obtain flow function.

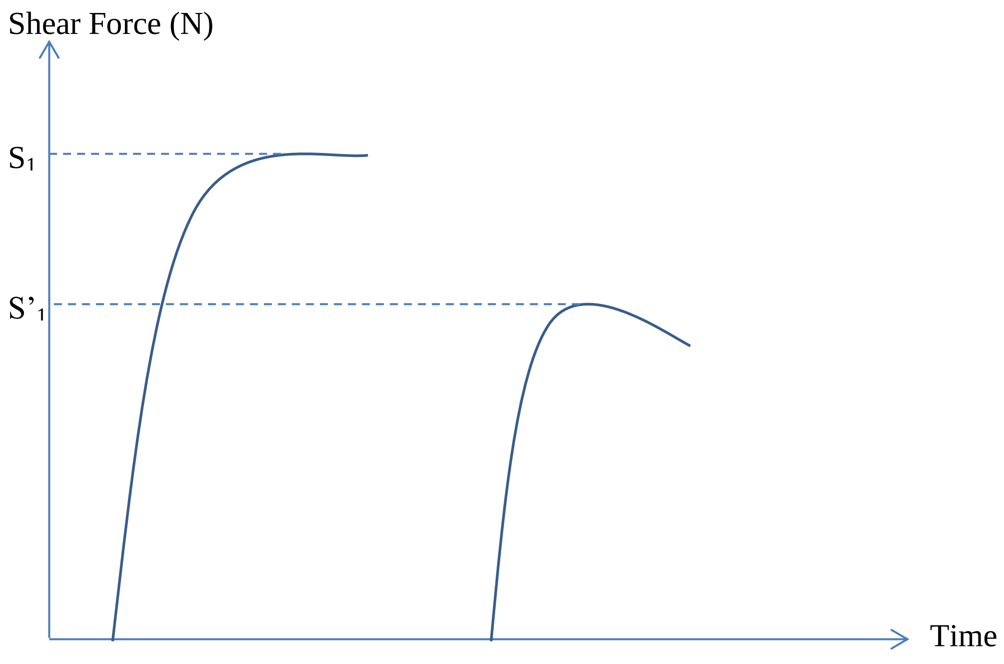


Figure 1.13: An example to experimental result of a shear test.

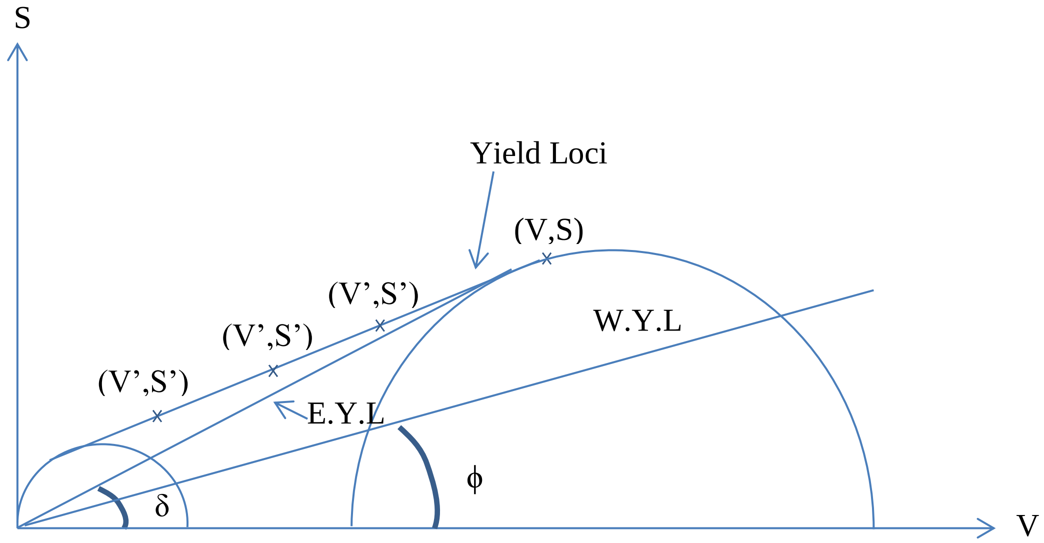


Figure 1.14: Yield loci, mohr circles and effective yield loci.

In the Figure 1.14, the line from origin to tangential to big semi-mohr circle gives the Effective yield locus, E.Y.L. The angle δ gives the effective angle of friction. The effective angle of friction is same for all yield locus, some minor changes can be observed.

The yield locus inform about how bulk flow internally. However in order to design a bulk material handling facility it is not just enough, we also need to know how bulk will flow on a wall surface. For this purpose wall friction experiments are made. Wall yield loci are independent from mohr circles (Figure 1.14). The angle between x axis and wall yield locus gives the kinematic angle of friction. Different wall liners give different yield loci and thus different kinematic angle of frictions (Figure 1.15).

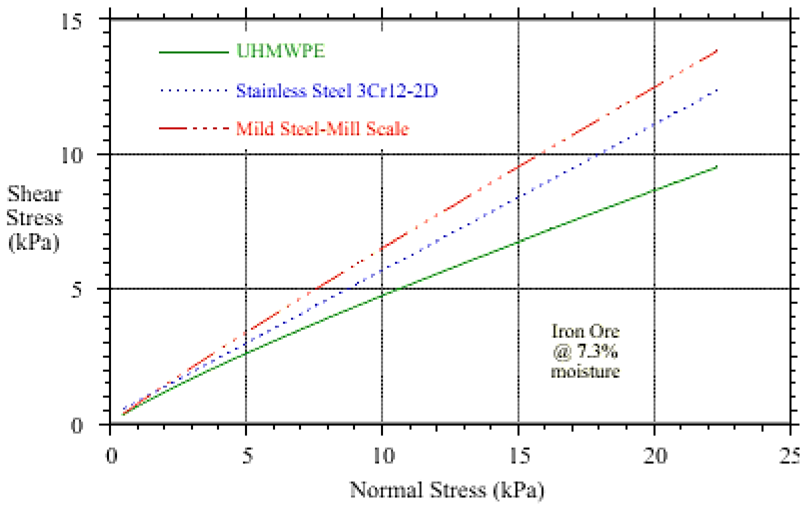


Figure 1.15: Different yield loci belong to different wall liners.

Choosing different wall liners can significantly promote flow, and change design. In figure 1.15 this effect can be seen, changing wall liner from mild steel to stainless steel cause almost 15 degree increment in hopper half angle. Figure 1.16. also gives an example to final result of a study of shear test for a hopper design, in conclusion hopper design parameters are obtained with shear test.

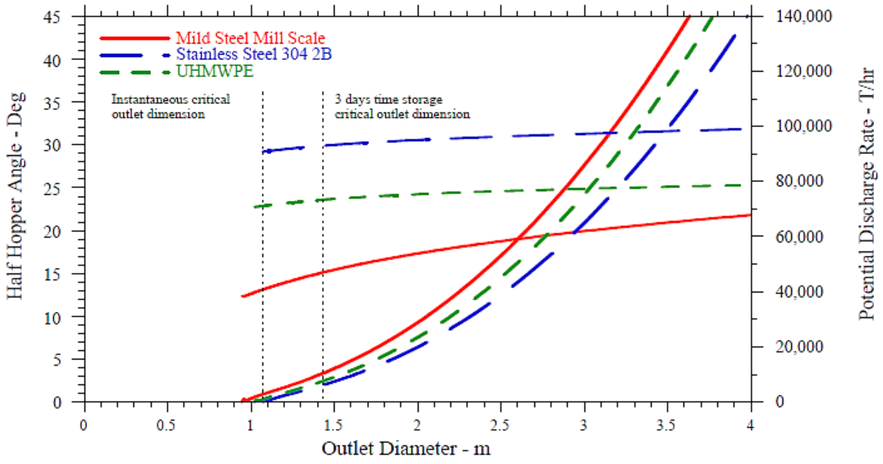
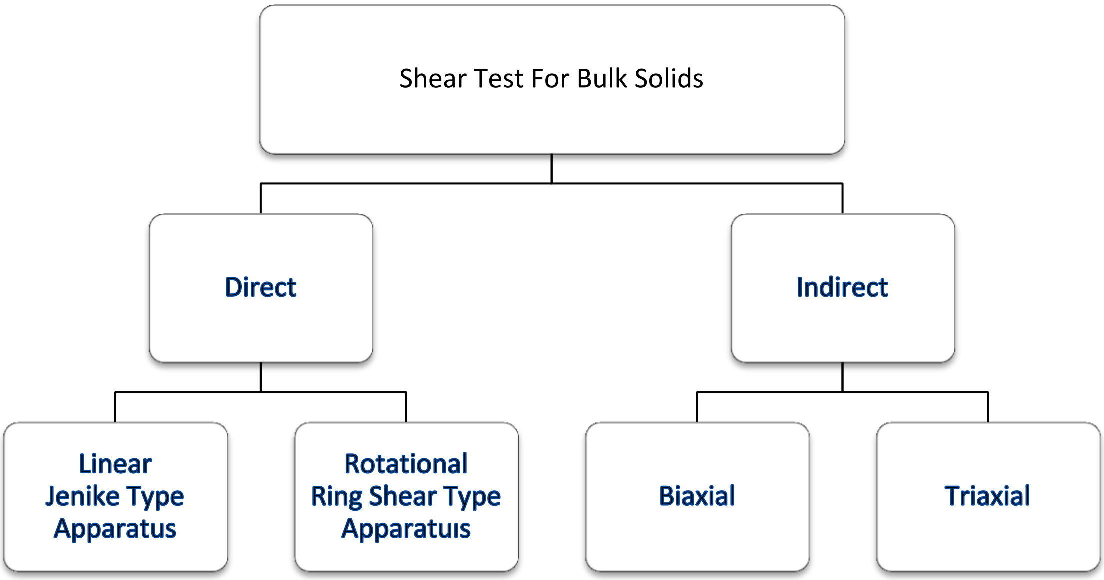


Figure 1.16: Outlet diameter vs. hopper half angle for different wall liners for a Hopper.

2. THE EXPERIMENTAL SETUP

There are different types of shear testers for bulk solids:

Table 2.1: Different types of shear testers (Arnold et al, 1980).



From the shear testers mentioned above the direct linear shear device Jenike Shear Tester is commonly used for most of the cases.

The vibrational shear tester is a modified version of conventional Jenike Style shear tester. In order to understand vibrational shear tester setup, firstly classic shear tester should be understood.

2.1 The Jenike Type Shear Tester

The aim of Jenike Type Shear Tester to measure the flow of material under different pressures which will allow an ultimate scale-up and direct engineers while designing stockpiles and silos.

Parts of the shear tester, and applied normal load, *V*, and shear force, *S*, are showed in Figure 2.1 (Roberts, 1998) **:**

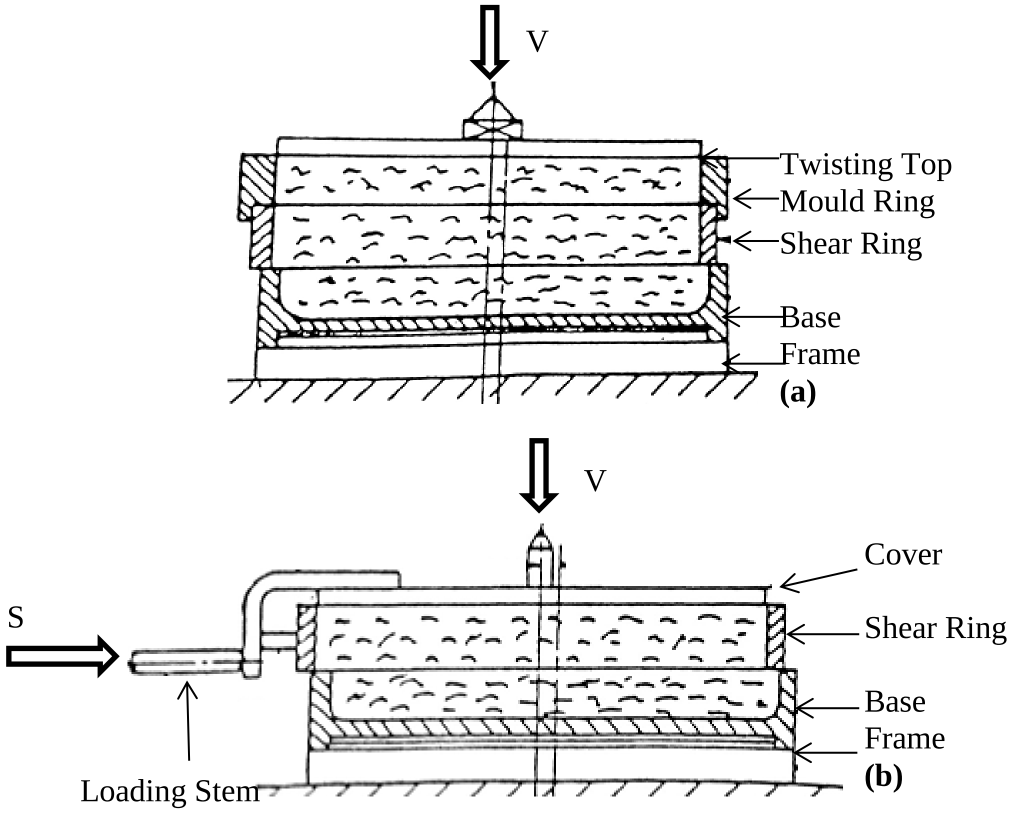


Figure 2.1: Parts of shear cell;b (a) During twisting, (b) During shear (Roberts, 1998).

The basic part of the shear tester is the shear cell. Shear cell consist of a base, a shear ring and a cover. The shear cell has a circular structure and it's inside diameter is either 95,3mm or 63,5 mm which makes possible to reach higher consolidation pressures during the experiment.

The mould ring and twisting top are only used during preconsolidation step which helps to form an uniform sample during experiment. A normal load is applied from the top of the cell and shear force is applied in horizontal direction. Shear force is produced by a load cell and transmitted to the shear ring by the loading stem. The shear ring slides on the base and shear the sample till the failure occurs. The loading stem has a constant strain rate so that the applied force changes during the experiment. It increases till the shear failure. After the failure it suddenly drops. Applied force is recorded in time domain and observed simultaneously by the operator.

The Jenike type shear tester makes easy to make the time consolidation tests with its small amount of sample.

The machine has four operating mode as fast forward, forward, reverse and fast reverse. The fast settings are only used between runs as an ease of operation.

The experimental testing procedures provide measurement of the following flow properties:

a) Effective angle of internal friction
b) Flow functions both instantaneous and after time storage
c) Kinematic angle of friction between the bulk solid and sample(s) of wall materials for mass flow bins
d) Extended Flow functions bot instantaneous and after time storage
e) Static angle of internal friction for funnel flow bins (Shear Testing Machine Operating instructions)

2.2 Rotational Ring Shear Apparatus

The Jenike Type Shear tester has limited space for shear. It is limited with the thickness of the shear ring. The rotational ring shear testers have conceptually unlimited travel, however they have the following disadvantages (Roberts, 1993):

- Because the particles stuff between the top and bottom part of the cell some inaccurate measurement may obtained
- Shear stress is obtained as function of radius because of the rotational motion and is not uniform for all regions of the sample
- Time consolidation tests are difficult to perform

2.3 Triaxial Test Apparatus

The triaxial test apparatus is not widely used for bulk material handling systems design. In triaxial test apparatus sample stored in a cylinder and the shear force applied from the top of the cylinder. It is not useful for time consolidation tests but gives better result for major consolidation stress because the concept of the test (Roberts, 1993).

2.4 Vibrational Shear Tester

The previous vibrational shear tester was built by Prof. Roberts,

The aim of the experiment is to observe the changes in shear force during vibration. In order to achieve this, an experimental setup is prepared with the following equipment according to the Figure 2.2. The vibrational shear tester contains a vibrational setup including: A function generator, an amplifier and an exciter, an accelerometer and data acquisition system.

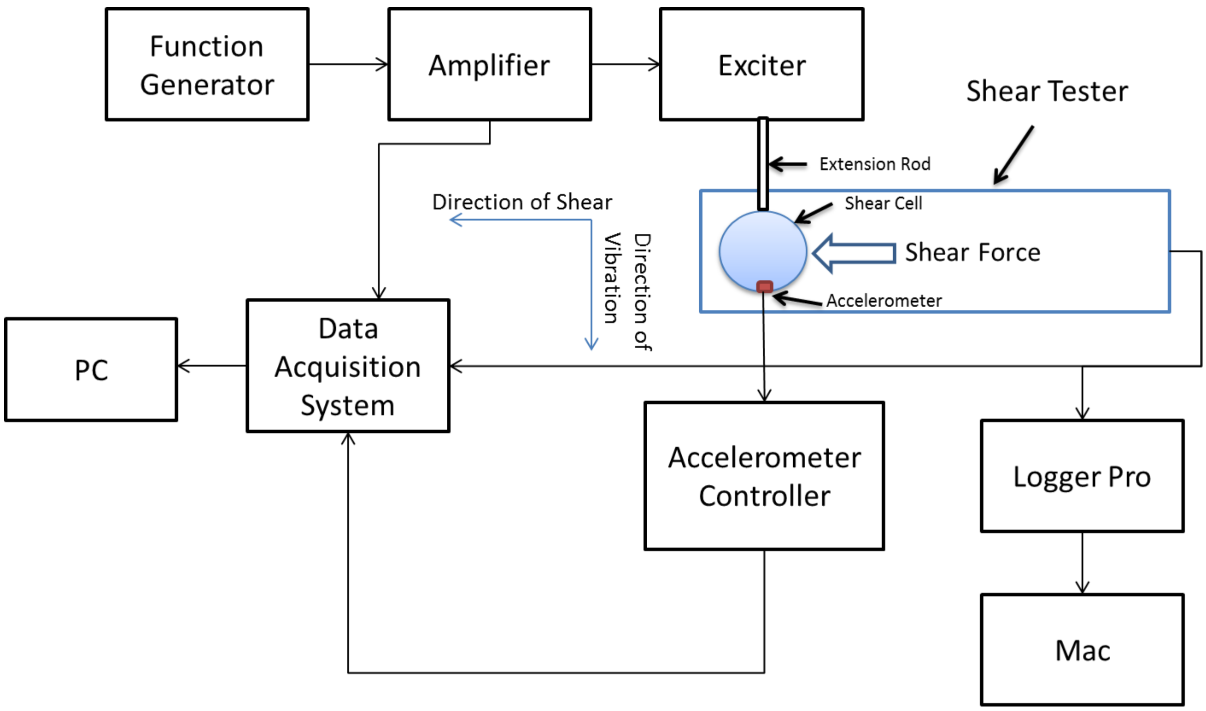


Figure 2.2: Scheme of the experimental setup.

Vibrational Equipments:

- Function Generator: Instek GFG8255A
- Amplifier: SmartAmp 2100E21
- The Exciter: The Modal Shop Inc. Model 2060E
- Data Acqusition System: Collect data from 6 different channels and transmit to PC
- Accelerometer: Records acceleration in the direction of X, Y, Z axis.
- PC: Records all the data with a user defined LabPro software.

Equipment belong to classic shear tester:

- Logger Pro: It is a device that convert analog signal to digital signal and transmit to Macintosh (Figure 2.3)
- Mac: There is special software as “FileMaker Pro” which is designed for evaluating shear tester outputs by TUNRA Bulk Solids. The software is not suitable for vibrational outputs thus MATLAB and MS Office Excel used for evaluation of data

Figure 2.3: Logger Pro.

As it is seen in the Figure 2.4 a function generator connected to an amplifier. The amplifier set the amplitude of the vibration in units of Volt. Thus, the amplitude of the exciter cannot be kept constant in a static / stable condition which was actually never possible during the experiment. The amplifier is also connected to data acquisition system in order to observe applied vibration as a double check. The accelerometer records the acceleration in X,Y,Z axis **(**Figure2.5, 2.6). The vibration is applied on Y direction therefore only Acceleration Y is taken into account for calculations. Also in some cases the X and Y accelerations are compared in order to observe the spreading of vibration. The shear tester is connected to Macintosh by LoggerPro as usual; also it is connected to PC in order to visualize shear and acceleration in same time domain. By a user defined LabWiev software a graph of all the data is obtained and observed simultaneously. (Figure 2.7) However the post processing of vibrational results was done with the software MATLAB and MS Office Excel.

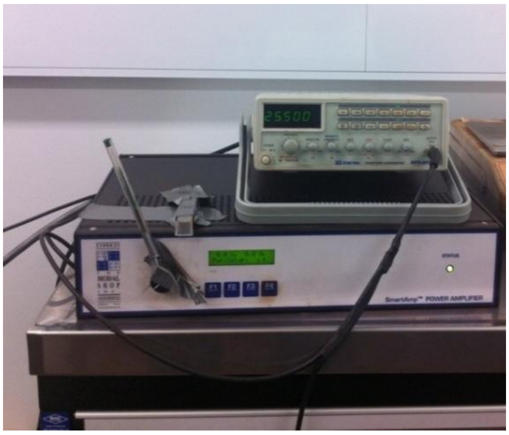


Figure 2.4: Function generator and amplifier.

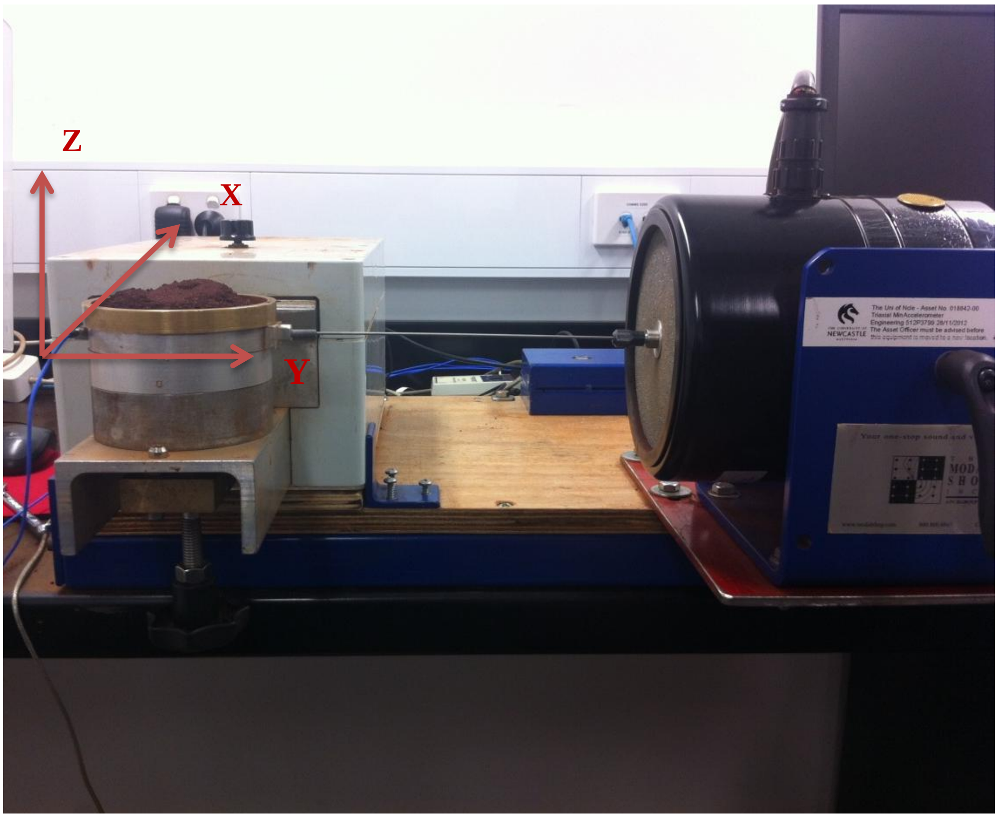


Figure 2.5: The shear tester, accelerometer, exciter and the acceleration directions.

Figure 2.6: A close look to accelerometer.

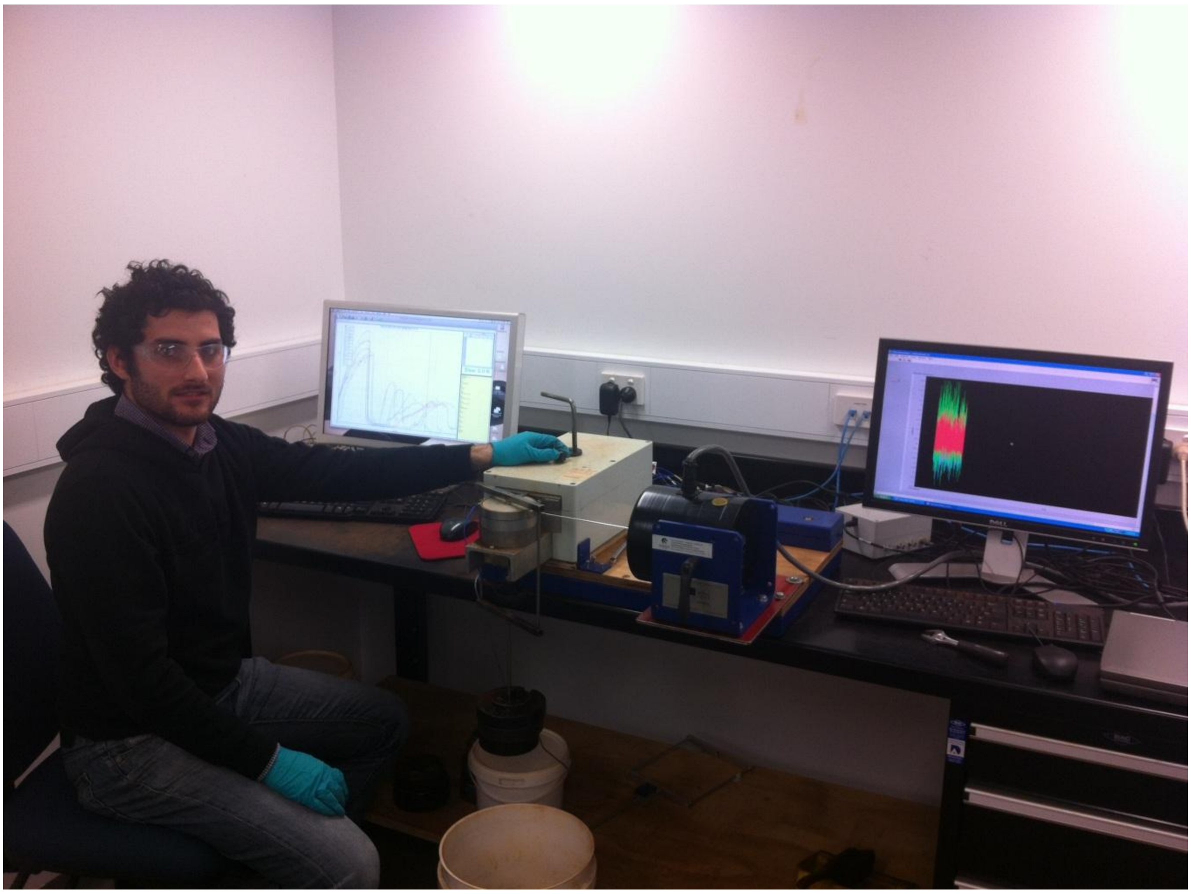


Figure 2.7: Author, experimental setup, shear results graphs, accelerometer graph.

The shear ring is modified in order to attach the exciters' extension rod and accelerometer. A mould is replaced on shear ring in order to connect exciter's rod. (Figure 2.8)

Figure 2.8: Extension rod of exciter screwed to shear cell.

5 different channels are connected to Data Acquisition System:

- Amplifier
- Shear Force
- Acceleration X
- Acceleration Y
- Acceleration Z

While the amplifier is connected to observe input frequency and amplitude, the Shear Tester is connected to determine when the failure zone occurs and what the vibration is at that time stamp.

2.4.1 Operation of vibrational shear tester

The operation of classic shear tester and evaluating the data is a subject of expertise because the test depends on the bulk material and the technician who makes the experiment. The technicians should have enough experience to overcome problems and perform regular tests. Some general problems: the sample for the experiment can segregate, different moistures can be observed in same sample, a reluctant force may be applied by technician during pre-consolidation step. Moreover technicians should be able to decide if a run is successful or not.

Beside the general difficultness of direct shear test, vibration causes a more complex structure and more variables. Therefore it makes harder and harder to perform a regular test. The operation of vibrational shear tester is declared below.

2.4.2 Pre-Consolidation

Pre-consolidation step is done almost as classic shear test. No vibration is applied. The only difference is mounting of extension rod of exciter. It should be mounted before the step otherwise the shear ring may turn and the seat may not correspond with extension rod. During twisting the shear ring should hold tightly in order to prevent rotation of shear ring and bending of extension rod.

2.4.3 Pre –Shear

In this study, no vibration is added on pre-shear stage. The carrier should hang in a diagonal position; it should not touch the extension rod. The Pre-Shear stage is done same as classic shear test.

2.4.4 Shear

This is the most challenging part of the experiment. First of all the carrier will vibrate and have tendency to touch extension rod; it is needed to be fixed. It is attached to machine surface with a simple sticky tape.

Small weights on the carrier subject to fall down due to vibration. If small weights, 0.5, 1.0, 1.5 kg, are being used it is recommended to put the weights directly onto shear cell instead of using the carrier with considering the weight of carrier, 0.5 kg.

After finishing pre-shear the operational steps continue as follows:

a) Place the normal load.
b) Settle the frequency from function generator.
c) Start the 'Vibrational Testing Software' from PC
d) Turn on the amplifier to 1.0 Volt which is suitable for most cases. Be sure that the cell vibrates under the normal load that. If it does not vibrate, you can increase the voltage until 5 Volt which is the limit for data acquisition system.
e) Turn the control of shear testing machine to forward. This step should be done just after the previous step. If there is too much distance between the stem and cell, FORWARD the stem for some distance before the previous step but do not let it to touch the cell
f) Observed the real-time graph and wait until the failure occurs.
g) Turn the control of shear testing machine to STOP
h) Pause the amplifier
i) Stop the recording of software by pressing the button 'STOP'

2.4.5 Challenges during the operation

Some challenges are observed during the experiment. They are tried to be overcame or minimized. The problems can be grouped as: Problems due to material, problem due to experimental setup.

2.4.5.1 Problems due to materials

Firstly a highly moisturized (16,9%) (worst case) coal sample used for experiment. Making an experiment under vibration was really hard because moisture immigration is observed. During the shear process the water starts to flood between shear ring and base. The immigration of moisture due to vibration is expected. It is also commonly observed in full scale operations such as a vibratory feeder. It would be wisely to use a moisturized material for experiments. However the results were probably erroneous because the moisture is one of the basic parameter that effect flowability. During classic or vibrational shear tests high attention is showed to keep the samples' moisture stable between the runs: The sample buckets' lid always keep closed. Consequently it is decided to change the material.

Secondly, a dry iron ore sample (3,2%) is used. The material cohesive stress was really low; in other words the particles weren't holding each other at all. When vibration is applied during shear, the fine particles started to flood and spread out. It is observed in most runs especially in higher frequencies. Therefore the material was changed again and finally Iron ore with %5.3 moisture is used.

2.4.5.2 Problems due to setup

a. Bending of extension rod

The shear ring has modified in order to mount the extension rod from exciter. The rod has a screw at the edge. The shear ring has modified with a screw bed. The road is screwed into that bed (Figure 2.8).

The maximum bending of the extension rod is 6^o degree. The rod is flexible and still transmits the vibration under bending. The bending causes vibration on X axis. The "Acceleration X" was also recorded and compared with "Acceleration Y" and in the most of the case, the acceleration X was lower. However it is still effective on resultant vibrational velocity thus it is also considered in calculations. Also it is guess that the bending increase the noise observed in accelerometer data.

Moreover bending causes a counter force on loading stem which can be significant in low shear stresses. The counter force is changing according to displacement of shear ring. The displacement of shear ring is so short that it is not simply possible to obtain a precise curve displacement vs. counter force under vibration. The counter-force due to bending is neglected because it is observed in all runs.

b. Fixing the amplitude

It was another issue that encountered during experiments. The amplifier set the amplitude in unit of Volt in other word it is a function of voltage. It is set by a gauge on the amplifier. The amplifier's screen is not sensitive enough to set the amplitude same number for each run. Thus the gauge was extended with a simple pen and a simple plastic is added onto way of pen to fix it easily in every run (Figure 2.9).

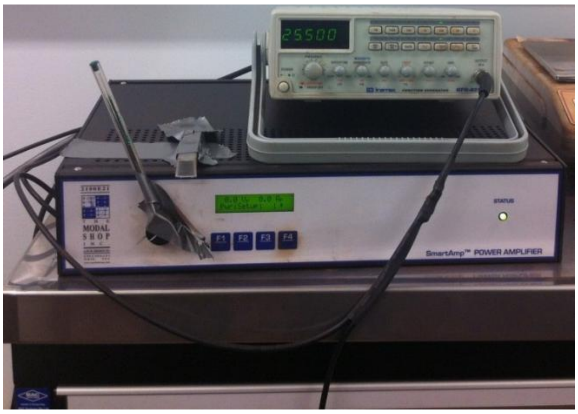


Figure 2.9: The gauge of amplifier.

This situation had not been expected. An observation was made for this problem. The shear ring was full and the normal loads applied. It is vibrated while the shear tester was not working. The acceleration is observed. The frequency was constant as it is expected, however the amplitude of acceleration was changing simultaneously.

It is only possible to overcome this issue with a control system. The acceleration of shear ring should be recorded by some sensor and the amplifier should be manipulated based on that on-line. However it is another subject of expertise thus it is not applied. Some other methods are applied in order to see the effect of amplitude in the results.

The failure is an event of a moment. In all experimental runs those moments (time stamps) were detected. The calculation was based on those time stamps. They are usually a second or a few. In addition all the comparisons were made on vibrational velocity to reflect the effect of amplitude. No comparison was made just depend on frequency.

3. DATA PROCESSING

Two different types of data are collected during the experiments. One is shear data the other one is vibrational data. The shear data is obtained by the traditional method. The shear tester is connected to a LoggerPro, a device convert analog signal to digital. After that connected to a computer and shear stress vs time graph is obtained.

Vibrational data is collected by accelerometer and transmitted to a PC to a user defined LabView software. This software stored acceleration in different axis, (Acceleration X, Acceleration Y, Acceleration Z) and shear force in time domain as a spreadsheet. The time domain has a frequency of 2000 Hertz.

The post process of raw data can separated into two groups, the process of vibrational data and the process of shear data.

3.1 The Process of Shear Data

As it is mentioned in previous chapter the main variables in shear tests are preshear load and shear load. The preshear load is kept constant and shear load is changed in order to obtain a yield locus. The preshear force should be same for each runs because same preshear load is applied. However this is not easy to achieve and usually some variations are observed. In order to overcome those variations normalization is applied.

An example of shear test results of three run is given in the Figure 3.1. Also some real results were shown in Appendix A. The preshear load is kept constant and the shear load is changed for those runs. The PS_1, PS_2, PS_3 shows the preshear stress and S_1, S_2, S_3 shows the corresponding shear stress. The average of PS_1, PS_2, and PS_3 gives the expected preshear stress. Firstly average PS is found (3.1) then Normalized Shear Force, "S^{norm}" is found (3.2).

$$\overline{PS} = \frac{\sum_{n=1}^{n} PS}{n} \tag{3.1}$$

$$S_x^{norm} = \frac{PS_x}{\overline{PS}} * S_x \tag{3.2}$$

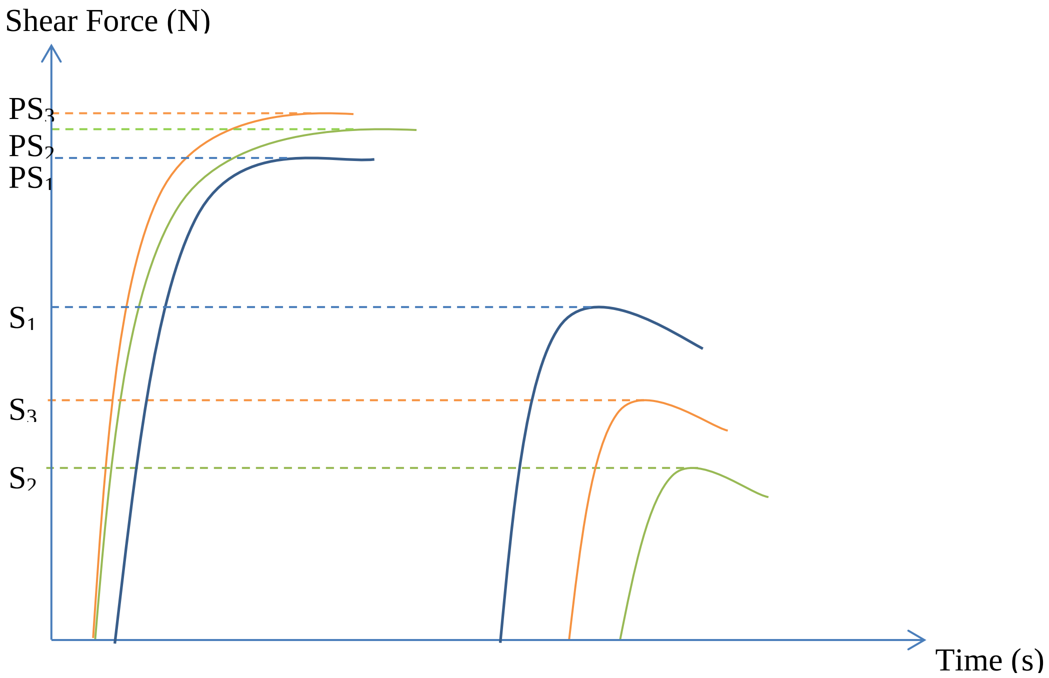


Figure 3.1: Shear test results.

After normalized shear force defined, the force values should be converted to stress values, S_{XPa}, in other words the units should be converted from Newton to Kilo-Pascal. The area of shear cell is 0,14 mm^2. Thus;

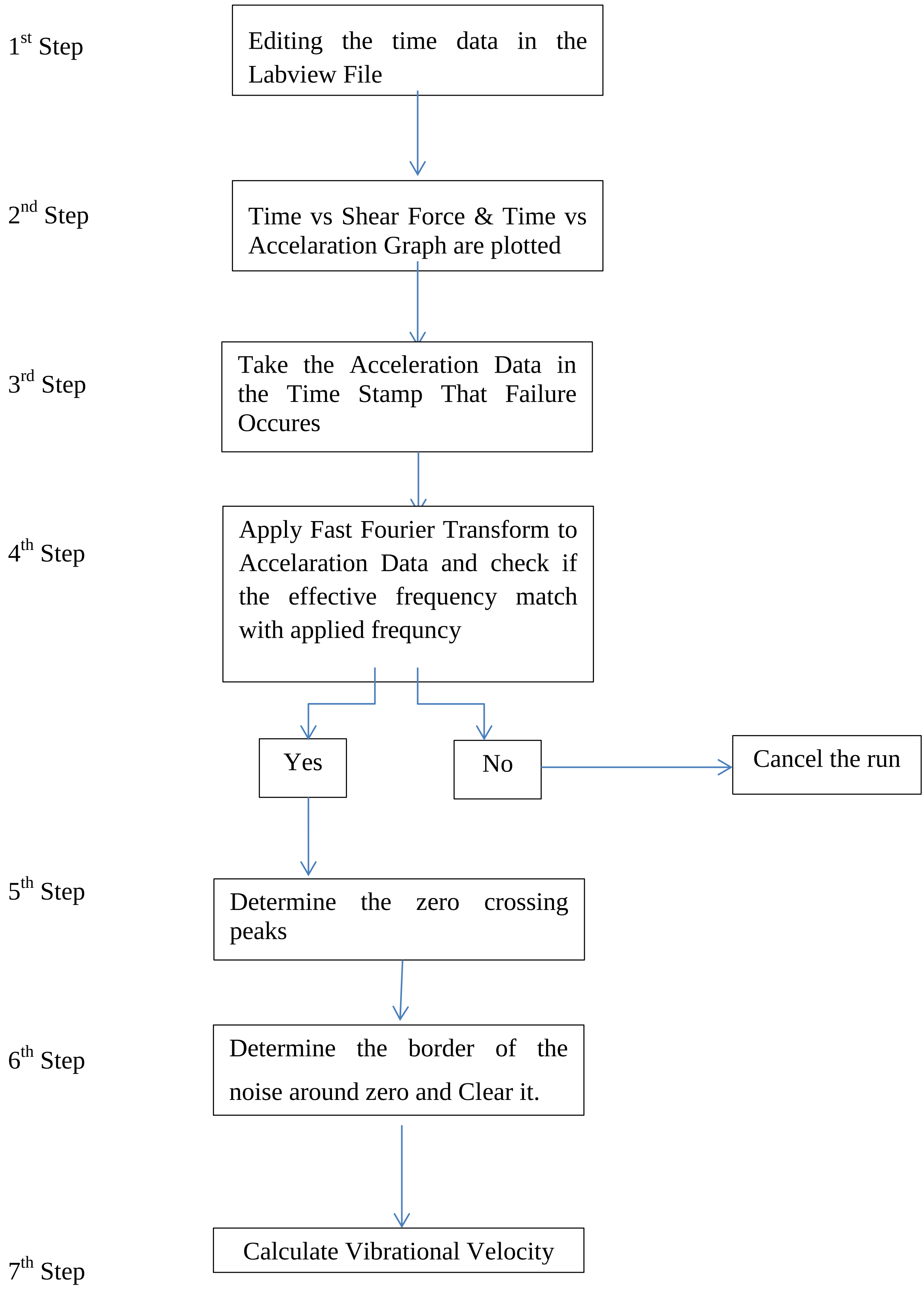
$$S_x^{norm(kPa)} = \frac{S_x^{norm}}{0,14} \tag{3.3}$$

During the experiment the weight of shear plane, WASP, should be measured and added to normal load so that effective normal force is obtained. After that, effective normal load is also converted to stress in order to obtain I.Y.L.

3.2 Process of Vibrational Data

The vibrational data was obtained from accelerometer during the shear procedure for each run. Lots of noise is observed in every run. It is needed to be clear. Also vibrational velocity should be calculated. All steps of processing vibrational data is shown in the flow sheet and explained with an example below (Table 3.1.).

Table 3.1: Flowsheet of processing of vibrational data.



1st step: Editing the time data in the Labview File

Labwiev is software used to design programs that collect data from laboratorial instrumentations. Simple software designed in Labview and information collected in spreadsheet format. An example output is seen in the screenshot (Figure 3.2). It belongs to a run with 2 kg Consolidation Load and 0,6 kg Shear load and 50 Hertz sinusoid vibration. The X value column represents time. The other channels represent the Acceleration Y X Z, shear force and Amplifier respectively.

	A	B	C	D	E	F	G	H	I
1	LabVIEW Measurement								
2	Writer_Version	2							
3	Reader_Version	2							
4	Separator	Tab							
5	Decimal_Separator	.							
6	Multi_Headings	No							
7	X_Columns	One							
8	Time_Pref	Absolute							
9	Operator	labtest							
10	Date	1/05/13							
11	Time	11:37.2							
12	***End_of_Header***								
13									
14	Channels	6							
15	Samples	1000	1000	1000	1000	1000	1000		
16	Date	1/05/13	1/05/13	1/05/13	1/05/13	1/05/13	1/05/13		
17	Time	11:37.2	11:37.2	11:37.2	11:37.2	11:37.2	11:37.2		
18	Y_Unit_Label	Volts	Volts	Volts	Volts	Volts	Volts		
19	X_Dimension	Time	Time	Time	Time	Time	Time		
20	X0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
21	Delta_X	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005		
22	***End_of_Header***								
23	X_Value	Voltage_0	Voltage_1	Voltage_2	Voltage_3	Voltage_4	Voltage_5	Comment	
24	0	-0.001165	0.950235	0.856071	0.932543	0.241167	1.402575		
25	0.0005	-0.006264	0.937485	0.881569	0.927443	0.243717	1.405125		
26	0.001	-0.001165	0.952785	0.901967	0.917243	0.225867	1.397474		
27	0.0015	0.006485	0.940035	0.924915	0.937643	0.241167	1.387273		
28	0.002	-0.003714	0.932385	0.935114	0.927443	0.243717	1.387273		
29	0.0025	-0.003714	0.911984	0.919816	0.907044	0.253917	1.400024		
30	0.003	-0.001165	0.866084	0.891768	0.917243	0.233517	1.397474		
31	0.0035	0.001385	0.906884	0.937664	0.904494	0.230967	1.389823		
32	0.004	0.001385	0.929835	0.907067	0.907044	0.243717	1.397474		
33	0.0045	-0.006264	0.937485	0.889218	0.935093	0.233517	1.405125		

run1

Hazır

Figure 3.2: Screenshot belong to output of a Matlab file.

The sampling rate is 2000 Hz, thus it is expected to have a time stamp for 0,005 second. However time data have some negative and unmeaning numbers. The reason of this simple problem either instrumentation or user defined program. Nevertheless, all the time data for each runs were edited.

2nd Step: Time vs Shear Force & Time vs Accelaration Graph Are Plotted

After the time column was edited, shear stress vs. time, acceleration vs. time graphs were plotted in MATLAB (Figure 3.3).

3rd Step: Take the Acceleration Data in the Time Stamp That Failure Occures

The measured acceleration is completely differs during the experiment as it is seen in the graph. Therefore in order to make the calculations the time stamp when the shear failure occurs was decided. For this run it was 55-60. The acceleration segment belong to 55-60 was separated

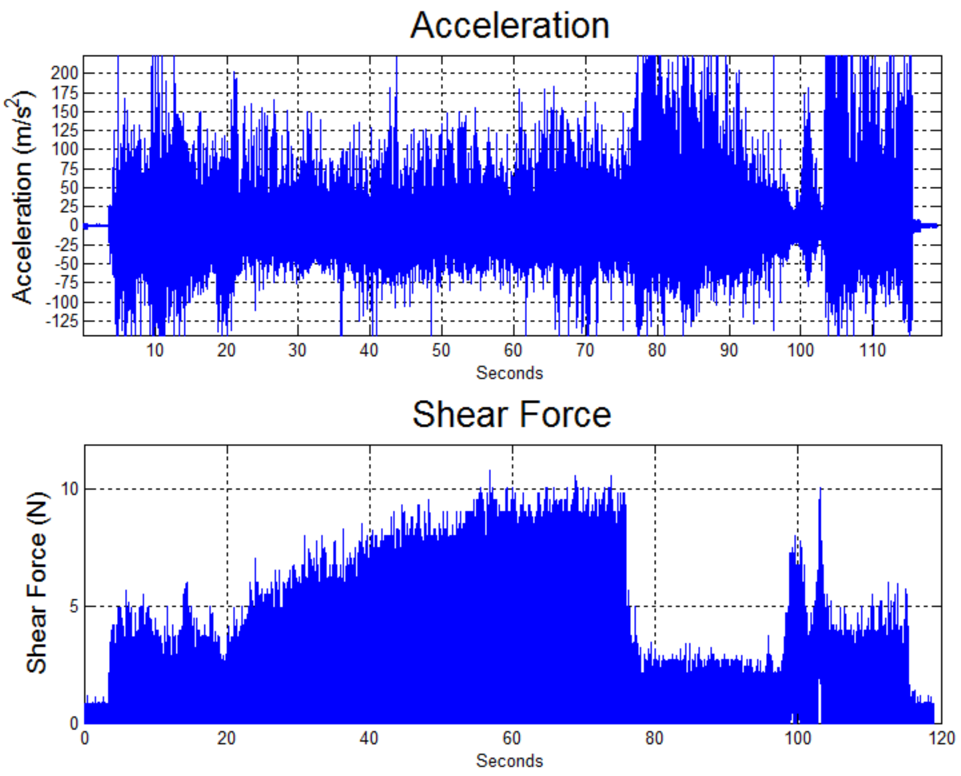


Figure 3.3: Acceleration and shear force vs time.

4th step: Apply Fast Fourier Transform to Accelaration Data and check if the effective frequency match with applied frequncy:

After time stamp decided Fast Fourier transform is applied to the acceleration segment. The aim is to figure out if the applied and measured frequencies are same. For this run as it is seen in the figure the effective vibration is 50 Hertz which is the applied vibration. In some runs different effective vibrations were observed and those runs were cancelled.

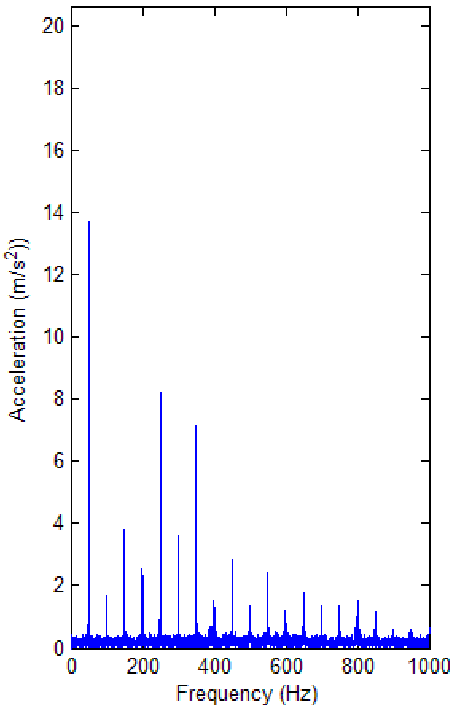


Figure 3.4: Fast Fourier Transform.

5th Step: Determine the zero crossing peaks

The zero crossing peaks of the acceleration segment were determined. The red circles and green crosses show the zero crossing peaks (Figure 3.5.). In every graphs similar peaks regimes are observed. There are some peaks and troughs on top and bottom, also some collected around zero. The peaks and troughs are collected around zero shows the noise. This noise should be cleaned to make accurate calculations.

6th Step: Determine the border of the noise around zero and Clear it

The peaks were collected in two different phases. One collection is around zero and the other one near to – 100 and + 100 (Figure 3.6a, 3.6b). A histogram of the peaks was plotted (Figure 3.7). The borders of the peaks around zero, which is also observed in every run, have determined and those peaks in the borders were deleted (Figure 3.8).

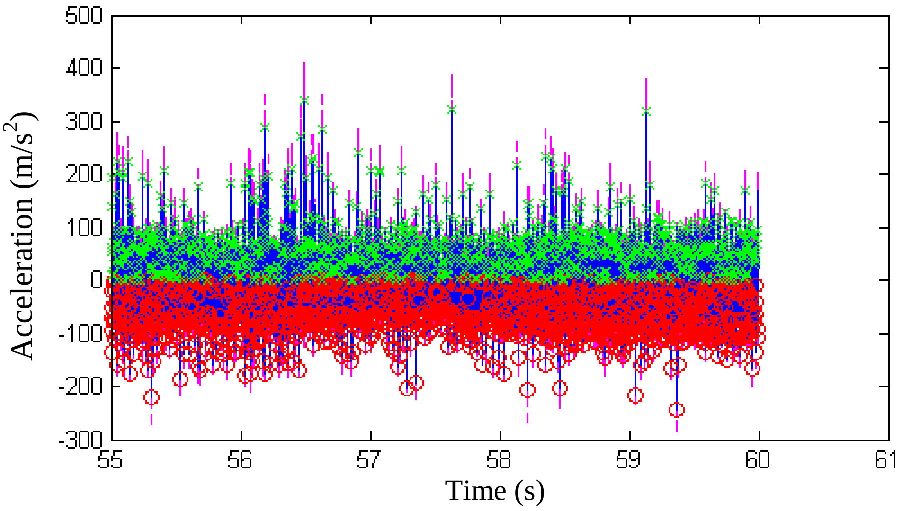


Figure 3.5: Accelaration (m/s^2) vs time.

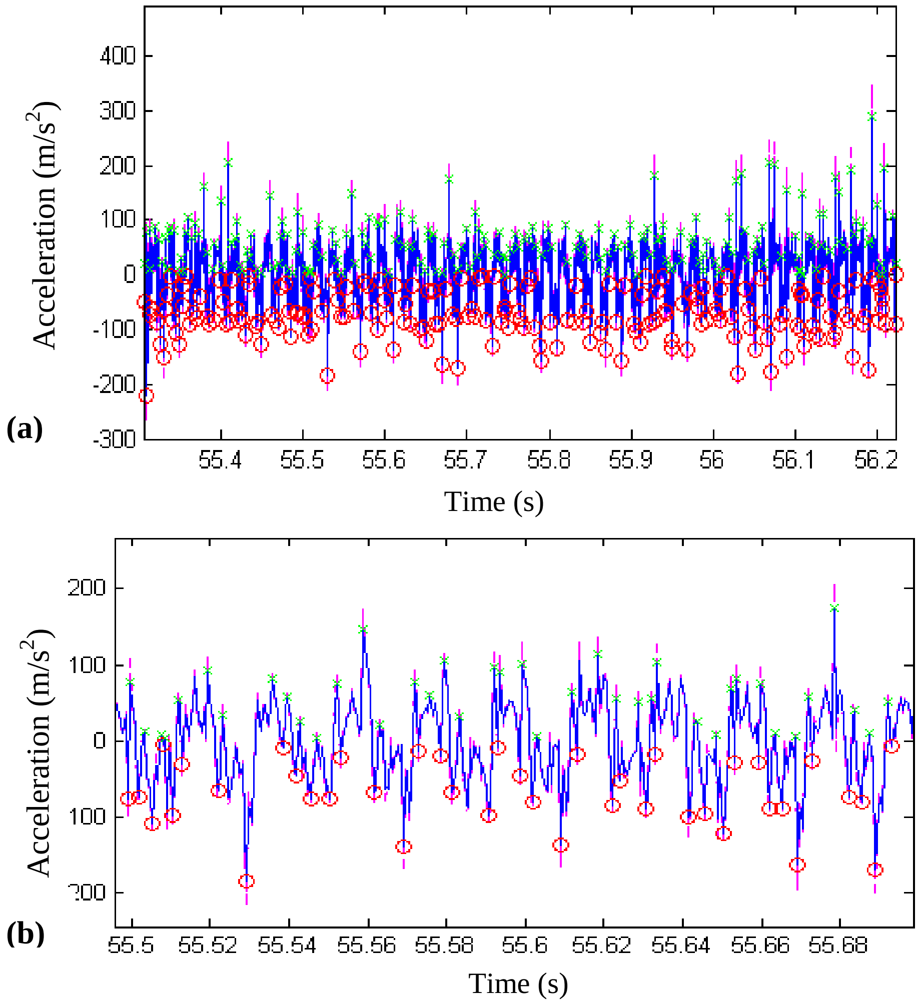


Figure 3.6: The peaks before clearing noise (acceleration vs time); (a) zoomed out, (b) zoomed in.

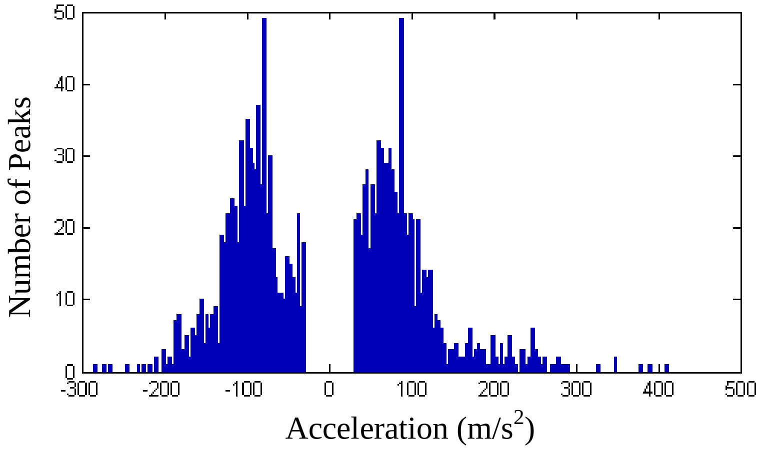


Figure 3.7: The histogram of the peaks after clearing noise.

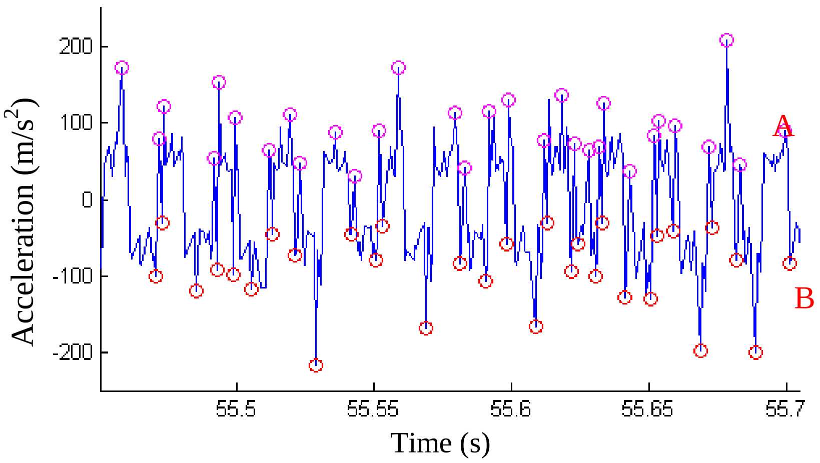


Figure 3.8: The peaks after clearing the noise.

No correlation was found between the determined borders(upper and lower) and the peaks in the histogram, which shows dominant vibration value, or max / min acceleration values. The max and min acceleration values are usually meaningless. Regardless all the data regarding noise clearing given in Appendix B. The tables B.1, B.2, B.3 presents the determined upper and lower borders for noise clearing, max and min acceleration values, dominant positive & negative acceleration values that obtained from histograms for each run.

7th Step Calculating velocity

In figure 6 the segment from Point A to Point B represents a part of acceleration. In order to obtain vibrational velocity from a sinusoidal acceleration we should divide the acceleration peaks and troughs (i.e. Point A and B) with 2.pi.f (derivative of acceleration). The new peaks and troughs values represent the vibrational velocity. In order to get average velocity magnitude of each segment calculated (i.e. a velocity peak+ a velocity trough (A+B)) then a mathematical average of those magnitudes is calculated.

Another good example, that belong to run PsL 2 kg, SL 0.1kg, 200 Hertz, is given below (Figure 3.9, 3.10, 3.11, 3.12). The time stamp decided as 40-43 seconds.

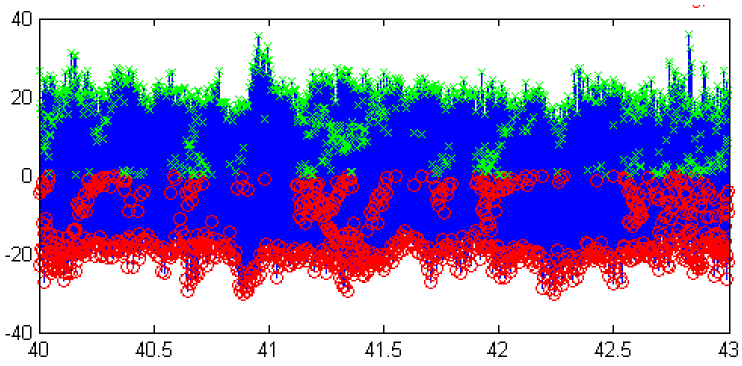


Figure 3.9: Peaks troughs before clearing noise.

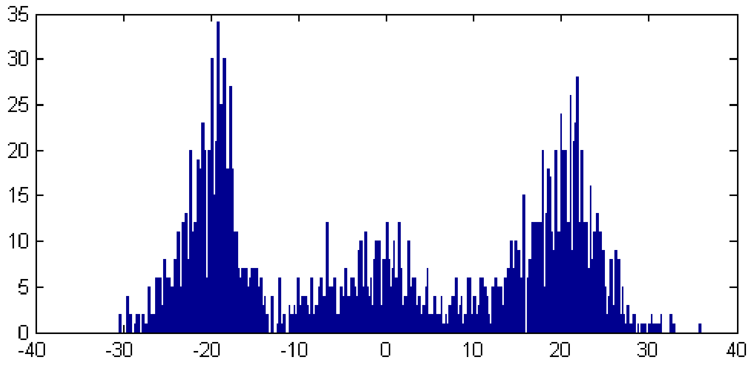


Figure 3.10: Histogram before clearing noise.

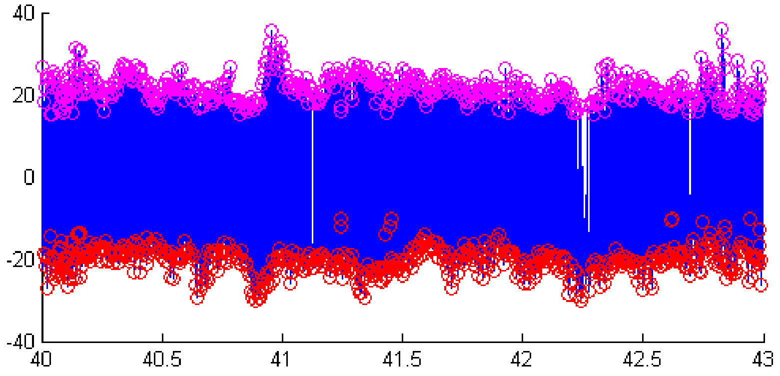


Figure 3.11: Peaks after clearing noise.

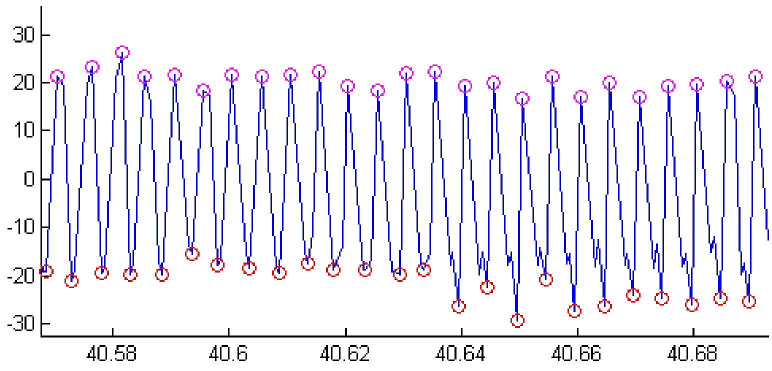


Figure 3.12: Peaks after clearing noise, zoomed in.

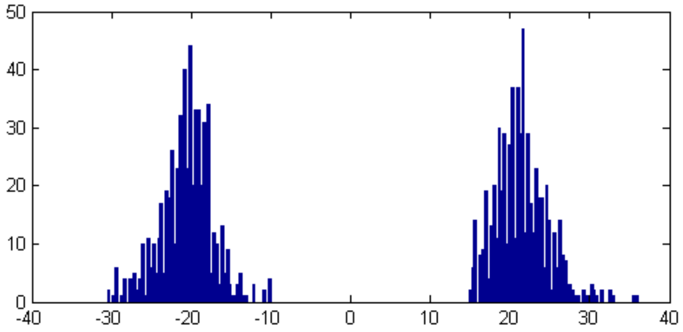


Figure 3.13: Histogram after clearing the noise.

4. EXPERIMENTS AND RESULTS

As it is mentioned in Chapter 2 an Iron ore sample (Hematite) with %5.3 moisture was chosen for the experiments. The particle size distribution is given in Figure 4.1.

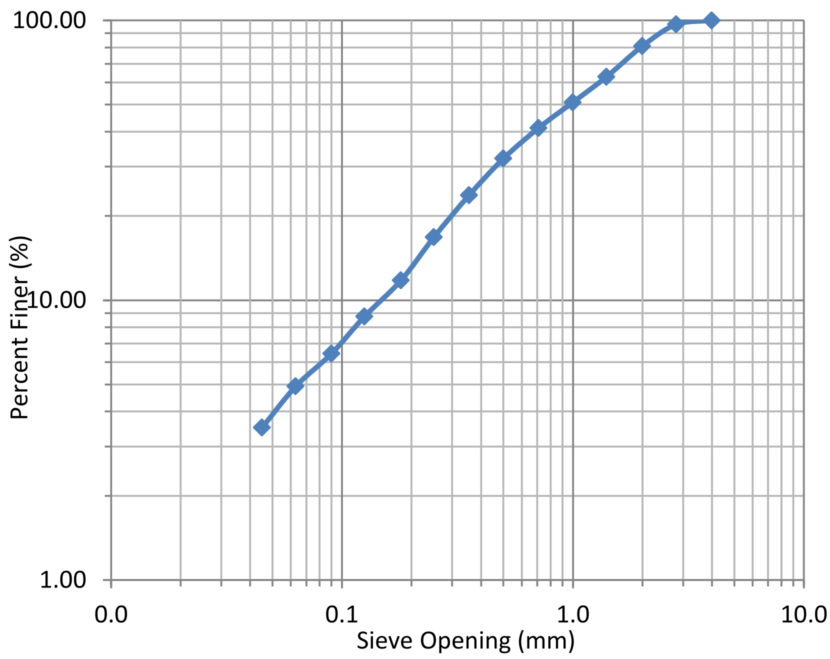


Figure 4.1: Particle size distribution of iron ore sample.

4.1 Experimental Method

In order to obtain a flow function minimum three preshear loads and for each preshear loads three shear loads are necessary. The experiments were decided according to that principle. For each preshear load and shear load, seven different frequencies, 0, 25, 50, 75, 100, 150 200, have been applied. Therefore sixty three experiments should have been made (Table 4.1).

Table 4.1: Number of experiments.

No of Pre-Shear Loads	3
No of Shear Loads	3
No of Frequencies	7
No of Experiments	63

However as it is expected in every experimental study, some data loss were observed and some useless data were obtained. The useless data is mostly because of vibrational data. Sometimes vibrational data could not record successfully. Also some runs were repeated for double check. Therefore information of 63 runs could not be reached, instead 55 successful run was obtained. The Table 4.2, 4.3, 4.4, shows the successful runs' input parameters

Table 4.2: Experiment runs belong to PsL 2 kg.

Preshear load	Shear load	Frequency
2	0.1	0
2	0.6	0
2	1.2	0
2	0.1	50
2	0.6	50
2	1.2	50
2	0.1	75
2	0.6	75
2	1.2	75
2	1.2	100
2	0.1	200
2	0.6	200
2	1.2	200
2	0.1	250
2	0.6	250
2	1.2	250

Table 4.3: Experiment runs belong to PsL 4.5 kg.

Preshear load	Shear load	Frequency
4.5	0.5	0
4.5	1.5	0
4.5	2.5	0
4.5	0.5	50
4.5	1.5	50
4.5	2.5	50
4.5	0.5	75
4.5	1.5	75
4.5	2.5	75
4.5	2.5	100

Table 4.3 (continued): Experiment runs belong to PsL 4.5 kg.

Preshear load	Shear load	Frequency
4.5	0.5	150
4.5	1.5	150
4.5	2.5	150
4.5	0.5	200
4.5	1.5	200
4.5	0.5	250
4.5	2.5	250

Table 4.4: Experiment runs belong to PsL 9 kg.

Preshear load	Shear load	Frequency
9	1.5	0
9	4.5	0
9	7.5	0
9	1.5	50
9	4.5	50
9	7.5	50
9	1.5	75
9	4.5	75
9	4.5	75
9	7.5	75
9	1.5	100
9	7.5	100
9	1.5	150
9	4.5	150
9	7.5	150
9	1.5	200
9	4.5	200
9	7.5	200
9	1.5	250
9	4.5	250
9	7.5	250

4.2 Experimental Results

The data has been processed as mentioned in previous chapter. The results are grouped as shear data and vibrational data in Chapter 3. The shear data: measured results, preshear stress and shear stress; calculated results, normalized shear stress which calculated with average preshear (see in Chapter 3). The vibrational data: Magnitude of resonant vibrational velocity (meausered). The comparison of shear stresses is made based on magnitude of resultant vibration velocities because it was not possible to keep the amplitude constant while changing the frequency (see in Chapter 2).

The results are given in Table 4.5, 4.6 and 4.7 as "Velocity"(Magnitude of Resonant Velocity) and "Normalized shear stress" $S^{norm(kPa)}$. In addition the vibrational velocity belong Y axis comparison with resonant velocity is given in Appendix C

Table 4.5: Experimental results belong to PsL 2 kg.

PsL (kg)	SL (kg)	Frequency	Resonant Velocity (m/s^2)	$S^{norm(kPa)}$
2	0.1	0	0.0	7.1
2	0.6	0	0.0	13.3
2	1.2	0	0.0	19.2
2	0.1	50	270.7	4.4
2	0.6	50	274.5	9.3
2	1.2	50	211.0	16.1
2	0.1	75	133.8	6.2
2	0.6	75	97.8	12.8
2	1.2	75	126.0	18.6
2	1.2	100	93.1	16.1
2	0.1	200	53.0	6.9
2	0.6	200	54.1	12.0
2	1.2	200	79.8	18.1
2	0.1	250	30.9	7.1
2	0.6	250	49.9	12.8
2	1.2	250	43.1	18.6

Table 4.6: Experimental results belong to PsL 4.5 kg.

PsL (kg)	SL (kg)	Frequency	Resonant Velocity (m/s^2)	$S^{norm(kPa)}$
4.5	0.5	0	0.0	13.9
4.5	1.5	0	0.0	24.9
4.5	2.5	0	0.0	36.4
4.5	0.5	50	181.6	11.2
4.5	1.5	50	136.6	22.5
4.5	2.5	50	92.3	31.8
4.5	0.5	75	160.7	14.0
4.5	1.5	75	118.0	20.7

Table 4.6 (continued): Experimental results belong to PsL 4.5 kg.

PsL (kg)	SL (kg)	Frequency	Resonant Velocity (m/s2)	Snorm(kPa)
4.5	2.5	75	241.5	27.5
4.5	2.5	100	112.1	32.1
4.5	0.5	150	53.1	9.6
4.5	1.5	150	74.9	20.8
4.5	2.5	150	96.7	33.9
4.5	0.5	200	61.6	12.2
4.5	1.5	200	55.5	21.5
4.5	0.5	250	27.0	12.1
4.5	2.5	250	30.6	34.0

Table 4.7: Experimental results belong to PsL 9kg.

PsL (kg)	SL (kg)	Frequency	Resonant Velocity (m/s^2)	$S^{norm(kPa)}$
9	1.5	0	0.0	28.3
9	4.5	0	0.0	54.1
9	7.5	0	0.0	88.5
9	1.5	50	182.7	20.5
9	4.5	50	34.5	50.9
9	7.5	50	164.0	89.7
9	1.5	75	148.3	19.5
9	4.5	75	64.6	53.7
9	4.5	75	60.4	53.7
9	7.5	75	39.0	86.2
9	1.5	100	194.3	18.4
9	7.5	100	224.3	75.9
9	1.5	150	59.1	21.1
9	4.5	150	100.0	46.6
9	7.5	150	67.0	87.3
9	1.5	200	108.7	23.0
9	4.5	200	81.4	48.4
9	7.5	200	116.6	81.5
9	1.5	250	44.5	27.7
9	4.5	250	38.2	53.6
9	7.5	250	26.3	87.3

4.3 Discussions

The graphs showing vibrational velocity vs. shear stress are the basic result of the experiments (Figure 4.2 to 4.12). The graphs are also plotted in group according to their pre-shear load (Figure 4.5, 4.9, 4.13). Shear stresses compared against velocity which is obtained from acceleration, because it is needed to reflect the effect of both frequency and amplitude.

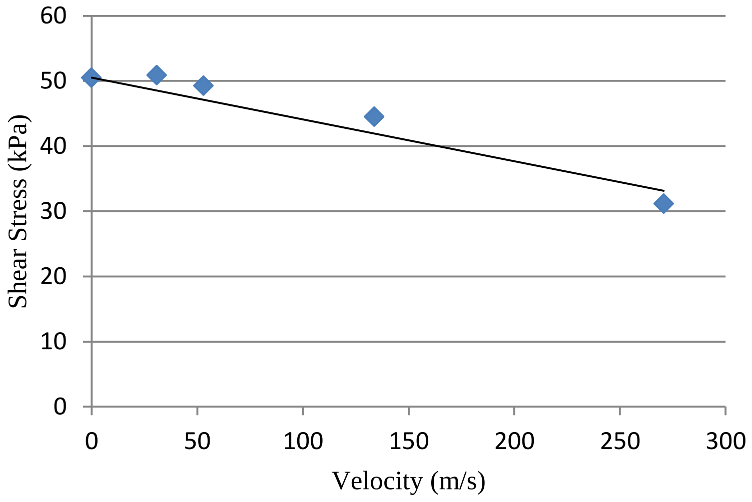


Figure 4.2: Velocity vs. shear stress; PsL for 2 kg, SL for 0.1 kg.

The figure 4.2 gives a good linear decrement. However the second data (30.9, 50.8), shows a little increment in the shear stresses. It is not expected and not possible. The shear stress only increase with really small vibrations. For example hammering the bin walls cause that. The speed of a hammer operation is probably less than 1 m/s. Therefore the second result is an experimental error.

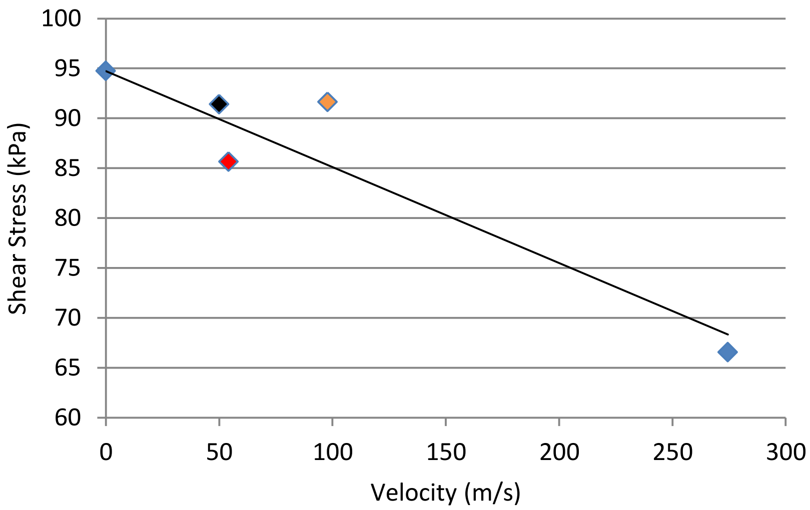


Figure 4.3: Velocity vs. shear stress; PsL for 2 kg SL for 0.6 kg.

In the Figure 4.3 there are two data do not fit with principle, increasing vibration velocity decrease the shear stress. Some little variations are observed. The fourth data, colored orange, (97.8, 91.6) is not really expected because with the increment of velocity it gives same shear stress with the second data, colored black (49.9, 91.4,). Also the third data, colored red, (54.1, 85.7) shows reduction in shear stress with almost same velocity. However both the points are definitely plausible.

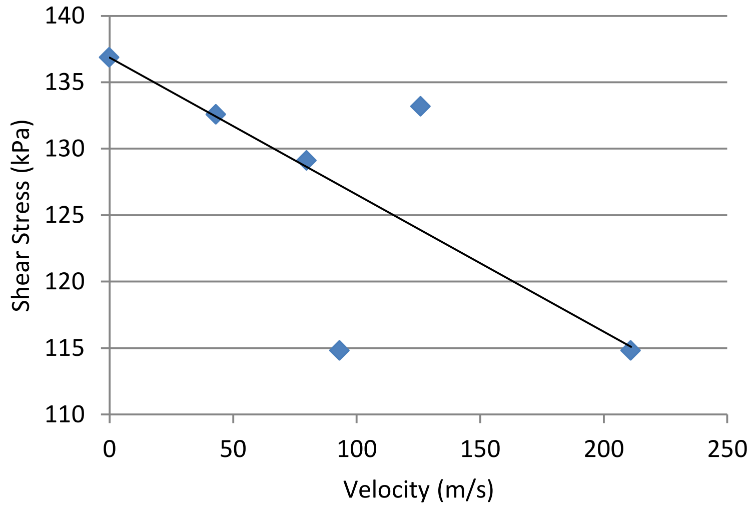


Figure 4.4: Velocity vs. shear stress; PsL for 2 kg, SL for 1.2 kg.

In figure 4.4 most of the data fit very well to the trend line. Only two data diverge, but they do not cause a crash.

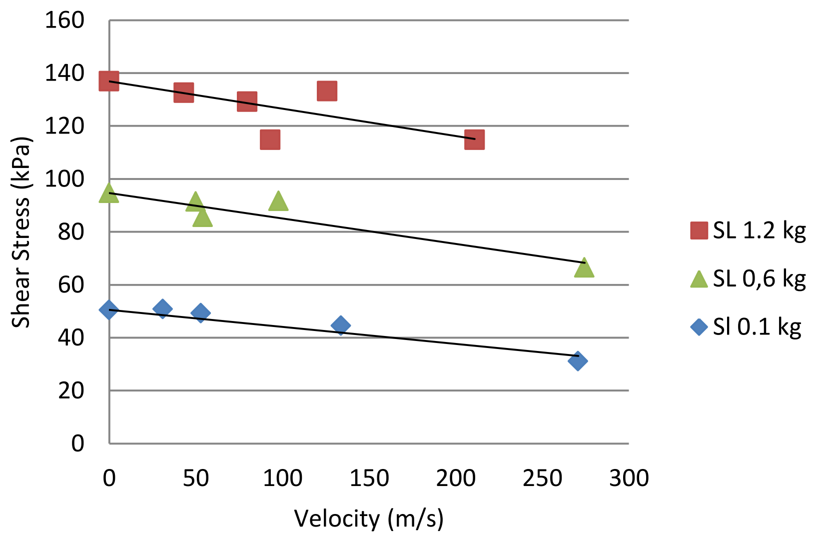


Figure 4.5: Velocity vs. shear stress; PsL for 2 kg; SL for 1.2 kg, 0.6 kg, and SL 0.1 kg.

Figure 4.5 shows three graph together belong to 2kg PsL and 1.2, 0.6, 0.1 kg SL , all three good trend line is observed with similar slope.

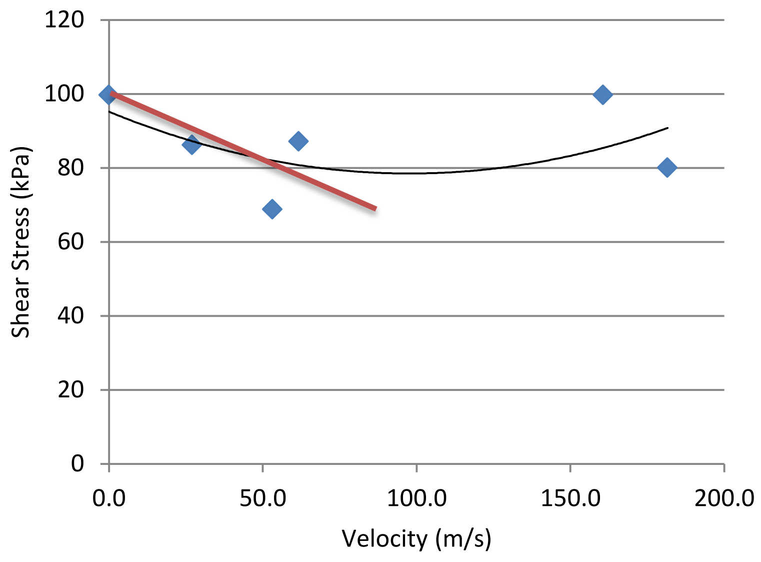


Figure 4.6: Velocity vs. shear stress; PsL for 4.5 kg, SL for 0.5 kg.

In figure 4.6 a polynomial trend ine is observed. It is not expected. When we look at the first half part of polynomial, the data tends to give a linear trend line, the red line. When the vibrational velocity increase from 50m/s to 150m/s high shear results are observed. The reason of that can be the small shear load. Because the small loads may move on the shear cell with the vibration, and can cause abnormality in the shear and vibration.

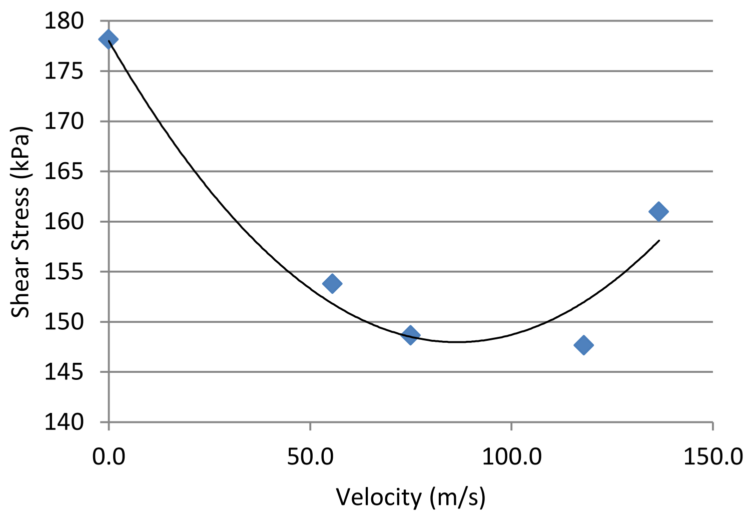


Figure 4.7: Velocity vs. shear stress; PsL for 4.5 kg, SL for1.5 kg.

The polynomial trend line is also observed in Figure 4.6. The last two data crashes a good linear trend line. The 1.5 kg shear load is not a small one thus it is not the same phenomena with Figure 4.5. The fourth data may be acceptable, but the fifth data is not acceptable. It can be an experimental error or because it is observed in two graphs, there may be some other phenomena which needs more focus in further studies.

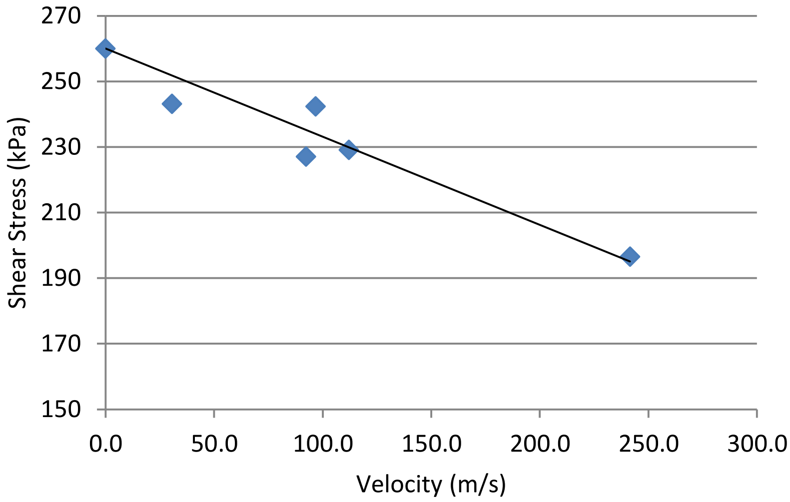


Figure 4.8: Velocity vs. shear stress; PsL for 4.5 kg SL for 2.5 kg.

In figure 4.8 a good linear trend line is observed.

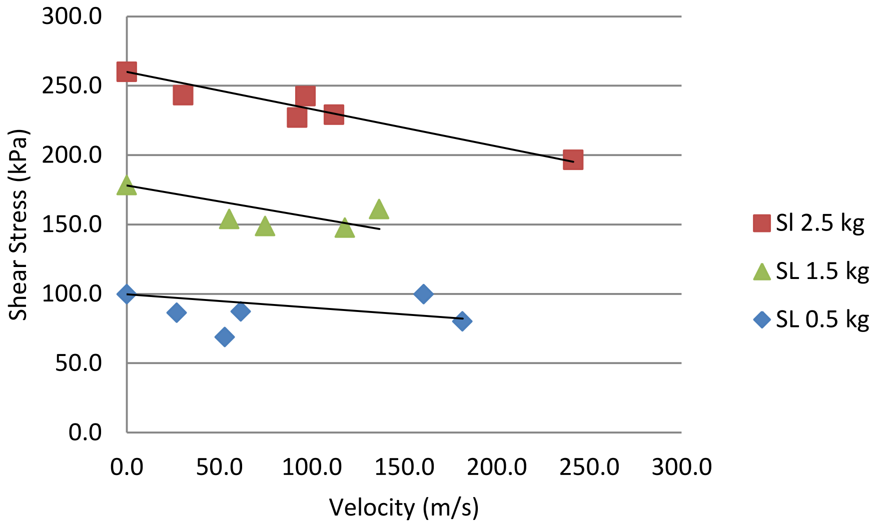


Figure 4.9: Velocity vs. shear stress - PsL for 4.5 kg; SL 2.5 kg , 1.5 kg, 0.5 kg.

In figure 4.9 all three graph belong PsL 4.5kg is shown in one. Only linear trend line is used. The PsL 2 kg gives almost parallel trend lines (Figure 4.5) Here especially the SL 0.5(blue dots), actually represented by a polynomial, crash that regime. The SL 1.5 kg also is represented by polynomial in Figure 4.7, however it may be acceptable as linear.

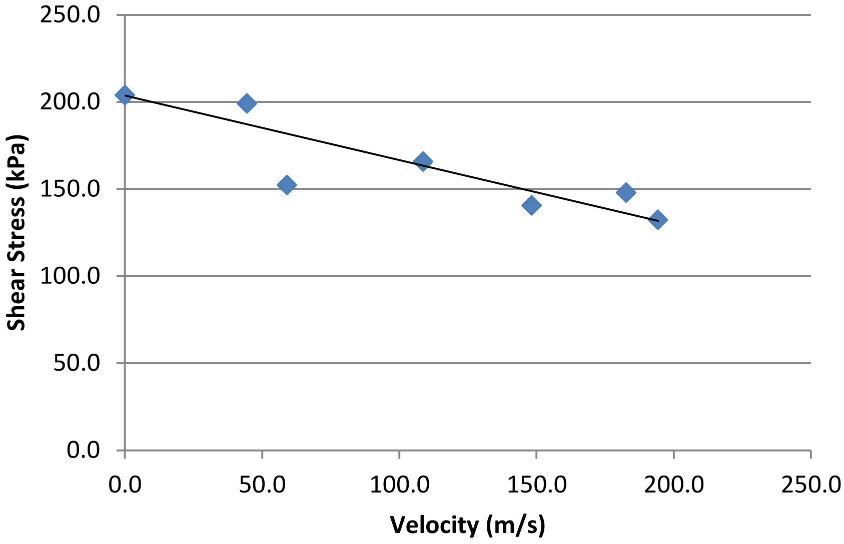


Figure 4.10: Velocity vs. shear stress; PsL for 9 kg, SL for 1,5 kg.

A successful trend line is observed in Figure 4.10

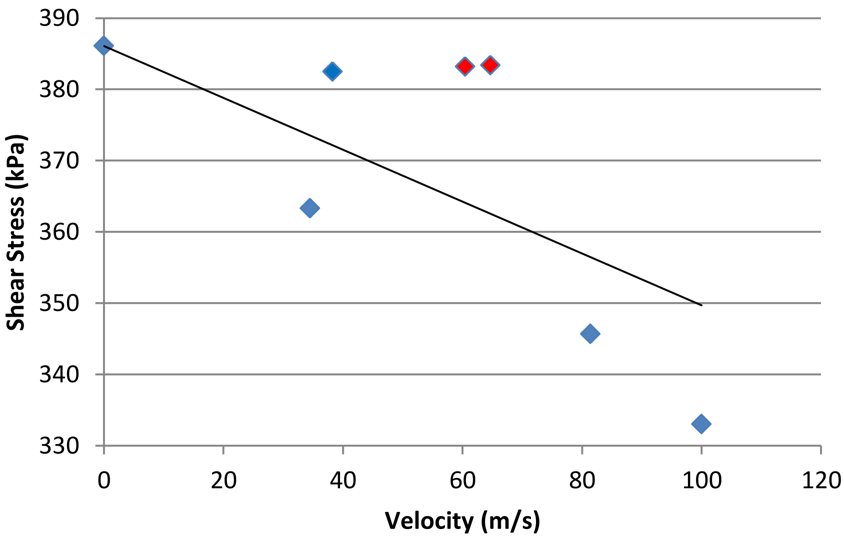


Figure 4.11: Velocity vs. shear stress; PsL for 9 kg, SL for 4.5 kg.

The figure 4.11 represents expectable results. There are three data that subject crash the linear trend line. The black one is still acceptable. The red dots are taking attention because their vibrational velocities and the corresponding shear stresses are almost same. In my opinion it is a proof to that the experiments and data processing are successful.

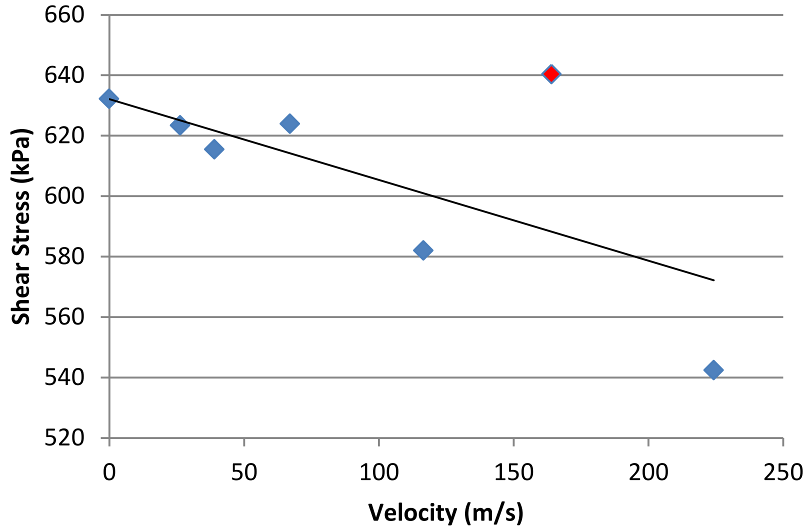


Figure 4.12: Velocity vs. shear stress; PsL for 9 kg, SL for 7.5 kg.

In figure 4.12 a good linear trend line is observed. Only one data, colored red, varies. This data can be neglected because the shear stress is higher than the non-vibration situation.

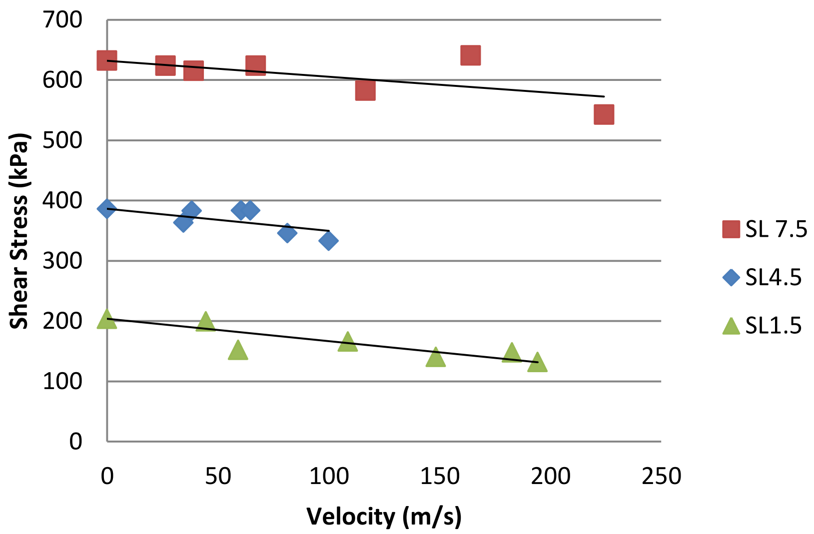


Figure 4.13: Velocity vs. shear stress; PsL for 9 kg; SL for 7.5kg, 4.5 kg, 1.5kg.

Figure 4.13 collects all the graphs belong to PsL 9 kg in one graph. Good linear trend lines are observed with similar slopes.

5. CONCLUSIONS

The aim of the study is to design an experimental setup that tests shear stress under vibration. In order to achieve this aim, a Jenike type shear tester is modified with vibrational equipment; a function generator, an amplifier, an exciter, an accelerometer. The vibrational setup has capability to vibrate the top half of the shear cell during shear procedure.

Several problems were encountered and overcame. The first problem was regarding the material. The experiment was done with a coal sample which has worst case moisture. The vibration causes water to immigrate and flood from the shear cell. The moisture is basic parameter that effect flowability of material. Therefore it wouldn't correct to compare vibrated and non-vibrated situation, since the material lose its moisture during the experiment. After that a dry (2.3% moisture) iron ore sample was used. This time the problem was the dryness of material. The cohesive force of the material was so low that the material does not hold each other and starts to flood from shear cell under vibration. After all, an iron ore sample is used with 5.3% moisture content which has enough moisture to hold itself and not too much moisture to cause water immigration.

The rod of exciter bends during the vibration. The bending is not more than 6 degree. The bending definitely causes a counter-force to shear. It is increasing with the displacement of shear ring. Because the displacement of shear ring is so short, it is not simply possible to obtain a precise correlation between them. Moreover the counter force observed in every run. Therefore it is neglected.

The amplitude of the system cannot fix with the existing equipment. The amplifier set the amplitude as Volt. Even though the same voltage applied for all the experiment different amplitude values were observed. The offered solutions were mentioned in Chapter 2. It was not possible to overcome this problem in the experimental setup. Therefore the results are compared according to vibrational velocity which is obtained from accelerometer data. The velocity is chosen as the basic variable because it contains both frequency and amplitude.

Experiments were done with 50, 75, 100, 150, 200, 250 Hertz. The graphs that compare vibrational velocity and shear stresses were plotted for different preshear and shear loads. The results show that shear stress decrease with the increase vibration and the decrement usually shows a linear trend.

Vibration usually use as flow promoter in hoppers. The results prove that vibration promotes flow. However in order to figure out how much vibration should be applied for different materials, more future studies should be made.

There are several options for future studies. Firstly, trying higher vibration velocities and observing if the linear trend continues or an asymptote occurs. In addition designing an experimental setup with fixed amplitude will give straight results about effect of frequency so that the results will be more applicable to industry. Moreover researching about how vibration spread in bulk material is another subject that takes attention. There are some theroical approaches in literature. Designing a pilot test rig and try to measure the spread of vibration can be a subject of PHD project.

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APPENDICES

APPENDIX A: Some shear test results.

APPENDIX B: Tables declares the determined noise clearing border for each run.

APPENDIX C: Tables declares the magnitude of velocity in Y axis.

APPENDIX A

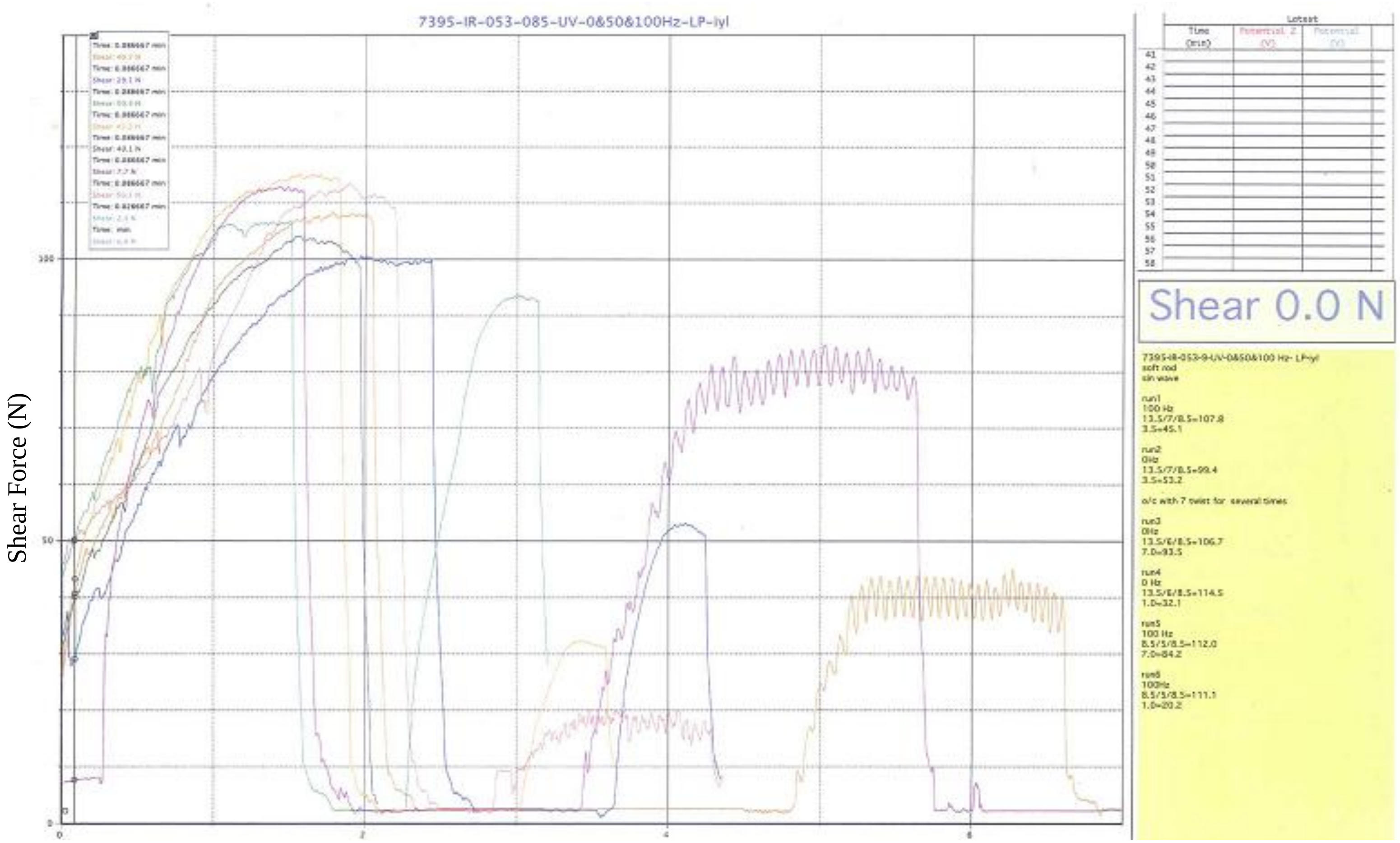
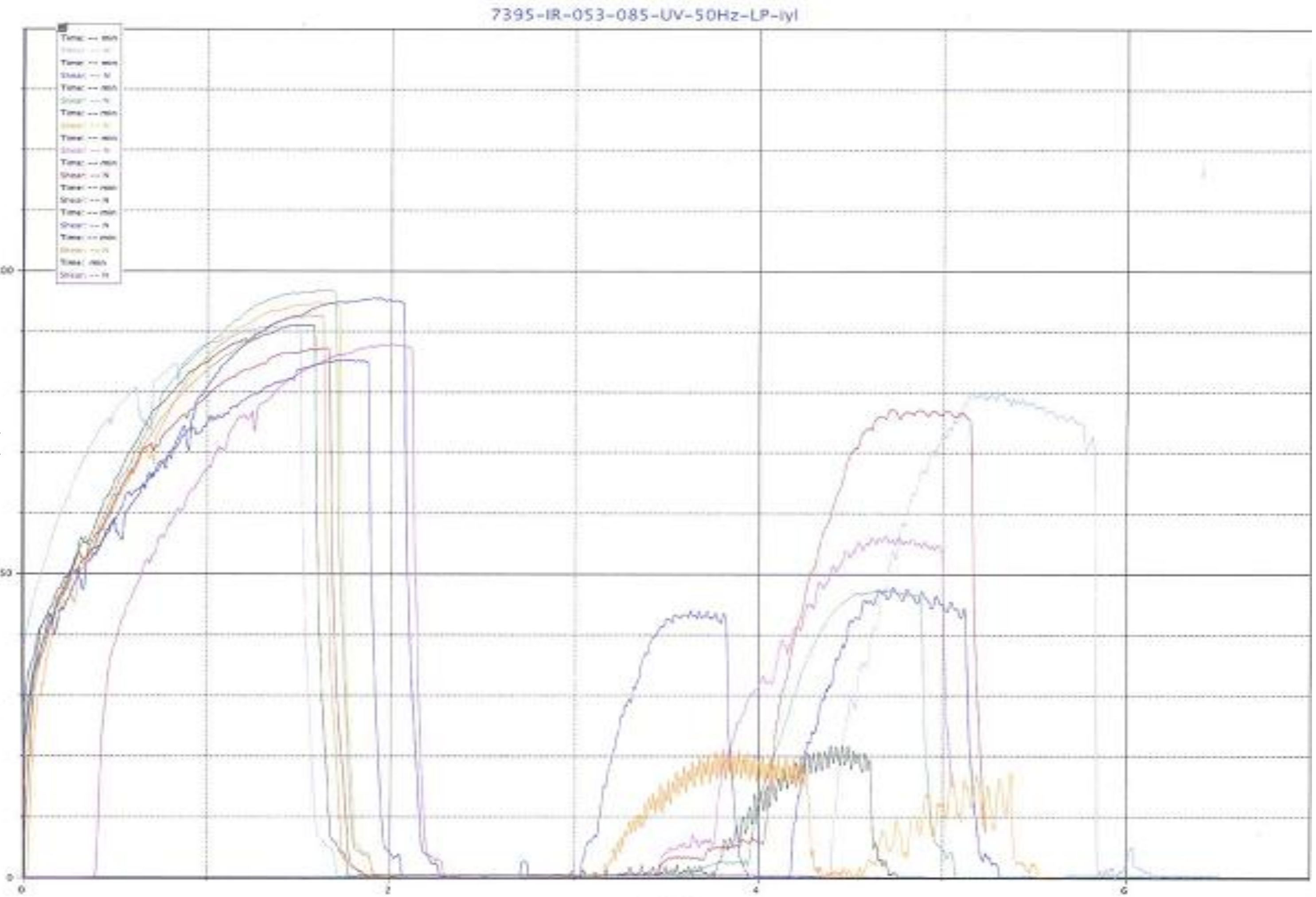


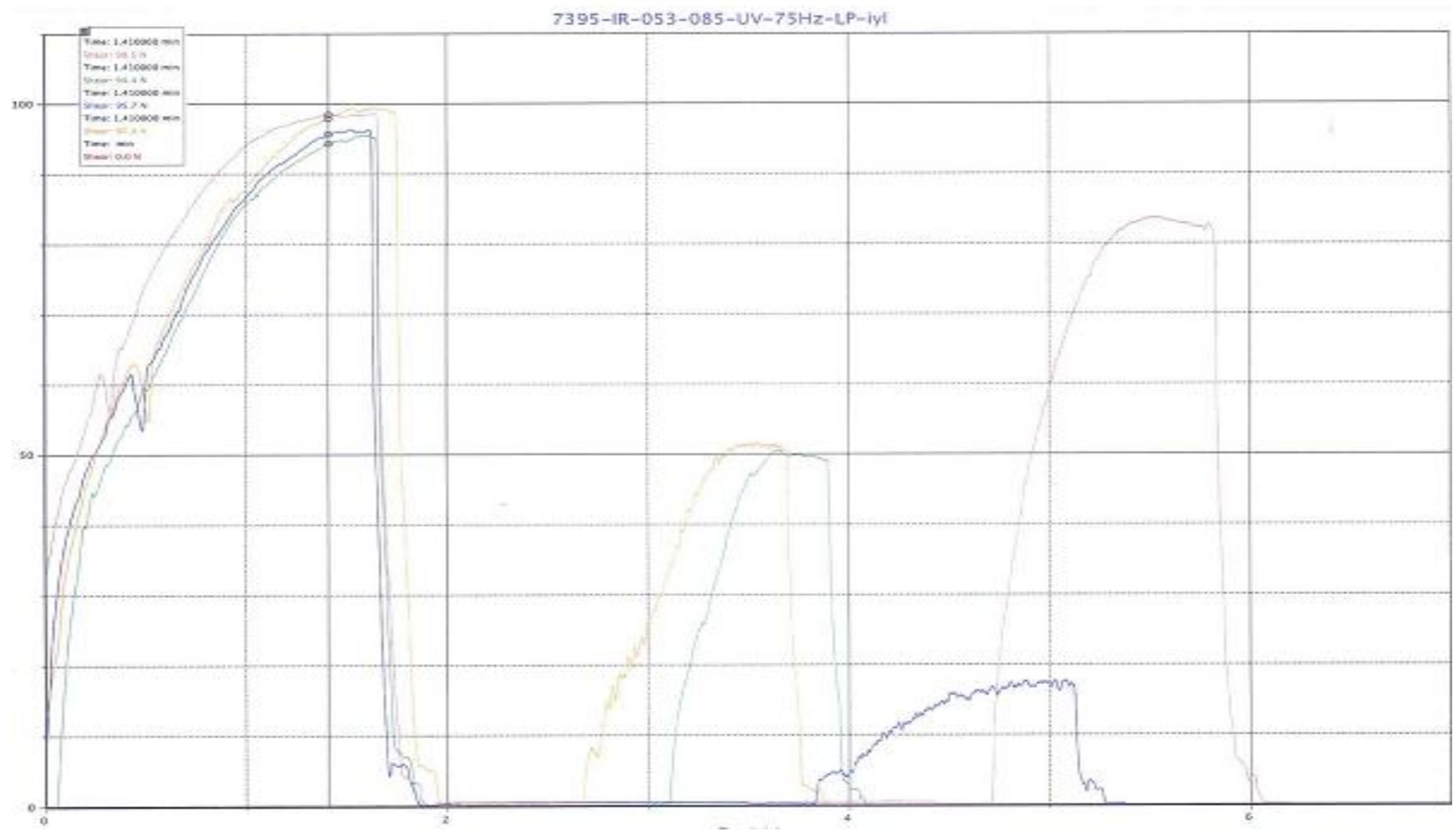
Figure A.1: Experimental results belong; PsL for 9 kg, for 0 Hz, 50 Hz 100Hz.



Shear Force (N)

Time (min.)

Figure A.2: Experimental results; PsL for 9 kg, 50 Hz.



Shear Force (N)

Time (min.)

Figure A.3: Experimental results; PsL for 9 kg, 75 Hz.

APPENDIX B

Table B.1: noise clearing information for Psl 2kg.

Preshear load	Shear load	Frequency (Hertz)	Lower Border	Upper Border	Hıstogram negative peak	Hıstogram positive peaks	Min Acceleration Value	Max Acceleration Value
2	0.1	50	-40	20	90	100.0	-520	540
2	0.6	50	-28	30	-28	30.0	-280	420
2	1.2	50	-25	27	-85	76.0	-258	270
2	0.1	75	-14	13	-56	48.0	-75	66
2	0.6	75	-10	15	-30	26.0	-135	110
2	1.2	75	-30	29	-42	32.0	-60	55
2	1.2	100	-15	20	-31	38.0	-60	80
2	0.1	200	-10	15	-20	22.0	-30	35
2	0.6	200	-14	8	-20	12.0	-92	115
2	1.2	200	-10	20	-28	28	-60	40.0
2	0.1	250	-7	3	-11	5	-40	36
2	0.6	250	-10	7	-15	14	-56	50.0
2	1.2	250	-12	7	-19	10	-26	21.0

Table B.2: Noise clearing information for PsL 4.5 kg.

Preshear load	Shear load	Frequency (Hertz)	Lower Border	Upper Border	Hıstogram negative peak	Hıstogram positive peaks	Min Acceleration Value	Max Acceleration Value
4.5	0.5	50	-5	5	-25	27	-100	273
4.5	1.5	50	-15	10.0	-45	40	-75	95
4.5	2.5	50	-5	5.0	-30	15	-123	110
4.5	0.5	75	-35	10	-52	55	-370	720
4.5	1.5	75	-15	16.0	-48	58	-70	66
4.5	2.5	75	-28	20.0	-65	52.0	-240	220
4.5	2.5	100	-15	15.0	-40	30.0	-100	75
4.5	0.5	150	-22	32.0	-60	62.0	-225	275
4.5	1.5	150	-22	18.0	-28	28.0	-41	40
4.5	2.5	150	-12	15.0	-53	45.0	-215	155
4.5	0.5	200	-20	10.0	-28	17.0	-40	35
4.5	1.5	200	-7	1.0	-35	35.0	-35	35
4.5	0.5	250	-4	7.0	-7	11.0	-17	16
4.5	2.5	250	-5	7.0	-10	10.0	-15	16.5

Table B.3: Noise Clearing Information for PsL 9 kg.

Preshear load	Shear load	Frequency (Hertz)	Lower Border	Upper Border	Histogram negative peak	Hıstogram positive peaks	Min Acceleration Value	Max Acceleration Value
9	1.5	50	-20	20.0	-55	-50	-240	230.0
9	4.5	50	-3	3	-10	11	-20	20
9	7.5	50	-20	20.0	-48	60	-98	85.0
9	1.5	75	-5	15	-25	45	-235	320
9	4.5	75	-10	10.0	-21	31	-40	42.0
9	4.5	75	-10	8.0	-68	31	-440	410.0
9	7.5	75	-5	5.0	-16	10	-60	40.0
9	1.5	100	-10	10.0	-60	40.0	-280	270
9	7.5	100	-60	5.0	-110	25	-400	200.0
9	1.5	150	-9	7.0	-30	18	-42	29.0
9	4.5	150	-10	25.0	-28	38	-100	110.0
9	7.5	150	-12	7.0	-26	19	-200	175.0
9	1.5	200	17	32.0	-48	74	-230	130.0
9	4.5	200	-50	35.0	-85	50	-135	65.0
9	7.5	200	-15	10.0	30	-40	-220	135.0
9	1.5	250	-5	8.0	15	-30	-40	20.0
9	4.5	250	-10	10.0	-16	18	-25	24.0
9	7.5	250	-5	5.0	-20	18	-24	22.0

APPENDIX C

Table C.1: Magnitude of Resonant Velocity and Velocity in Y axis

Preshear load	Shear load	Frequency	Resonant Velocity (m/s2)	Velocity in Y axis (m/s)
2	0.1	50	270.7	210.7
2	0.6	50	274.5	192.8
2	1.2	50	211.0	172.0
2	0.1	75	133.8	106.7
2	0.6	75	97.8	84.5
2	1.2	75	126.0	101.3
2	1.2	100	93.1	77.6
2	0.1	200	53.0	41.9
2	0.6	200	54.1	40.0
2	1.2	200	79.8	63.8
2	0.1	250	30.9	24.9
2	0.6	250	49.9	36.8
2	1.2	250	43.1	31.4
4.5	0.5	50	181.6	146.6
4.5	1.5	50	136.6	111.1
4.5	2.5	50	92.3	77.7
4.5	0.5	75	160.7	123.3
4.5	1.5	75	118.0	97.0
4.5	2.5	75	241.5	194.0
4.5	2.5	100	112.1	95.6
4.5	0.5	150	53.1	44.4
4.5	1.5	150	74.9	55.4
4.5	2.5	150	96.7	76.0
4.5	0.5	200	61.6	49.0
4.5	1.5	200	55.5	47.2
4.5	0.5	250	27.0	19.8
4.5	2.5	250	30.6	20.7
9	1.5	50	182.7	131.0
9	4.5	50	34.5	26.9
9	7.5	50	164.0	141.4
9	1.5	75	148.3	128.6
9	4.5	75	64.6	52.1
9	7.5	75	39.0	34.2
9	1.5	100	194.3	184.0
9	7.5	100	224.3	155.8
9	1.5	150	59.1	44.6
9	4.5	150	100.0	82.4
9	7.5	150	67.0	52.3
9	1.5	200	108.7	91.3
9	4.5	200	81.4	73.4

Table C.1(continued): Magnitude of Resonant Velocity and Velocity in Y axis

Preshear load	Shear load	Frequency	Resonant Velocity (m/s2)	Velocity in Y axis (m/s)
9	7.5	200	116.6	77.8
9	1.5	250	44.5	38.5
9	4.5	250	38.2	33.3
9	7.5	250	26.3	20.3

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