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Development of Circular Economy Routes for Refractory Waste

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Summary:
Refractory materials have the ability to withstand high temperatures without damaging their properties. They are used to protect production processes while maintaining their characteristics in extreme conditions. However, when they reach the end of their lifespan, these materials are usually discarded and dumped in landfills. This is harmful to the environment because landfills produce toxic leaches that can pollute groundwater and generate GHG emissions. Therefore, it is important to recycle these materials to reduce environmental harm. Before recycling any materials, it is crucial to analyze the particle size distribution of the waste materials to determine their properties and behavior in different conditions. In this thesis, the focus is on developing circular economy routes for steel and cement refractories. The particle size distribution analysis was conducted using a cross-flow air classifier and sieving to separate particles. The performance of the classifier was evaluated at three different air velocities (8,12,14m/s) and it was found that the separation performance was good when the sample had a size range of 5mm to 0.25mm. However, the classifier's performance degraded when performed on a narrow size range (1 to 3mm and 0.5 to 1mm) for both cement and steel samples. This particle size distribution analysis is important for later chemical analysis and testing to understand the waste materials' properties and enable their recycling for further use.

Preface

The thesis entitled ”Development of Circular Economy Routes for Refractory Waste” is a compulsory course of the Master of Science Energy and Environmental Technology (EET) in the faculty of Technology of the University of South-Eastern Norway (USN).
The reason behind choosing this thesis is that one of my areas of interest is the Recycling process. This thesis helped me to get an understanding of recycling refractory materials waste which is essential for environmental aspects. I got to know the technologies and methodologies behind this process and I am happy that I got the opportunity to work on this topic.
I am greatly thankful to Prof. Dr. Chandana Ratnayake for giving me this opportunity and the guidance that needed to complete this thesis on time. I would also like to thank Franz Otto von Hafenbrädl and Kristin Søiland from SINTEF Industry for providing me with the necessary information and helping me regarding the experimental process.
Lastly, I would like to thank my family and friends for supporting me through this journey. Especially my parents and elder sisters who continuously gave me support throughout this master’s degree.

Porsgrunn, 15th May 2023

Sheikh Saimon Ahamed Abir

Contents

List of Figures

List of Tables

Abbreviation

GHG	Green House Gas
CE	Circular Economy
LIBS	Laser Induced Breakdown Spectroscopy
FB	Fluidized Bed
EF	Electrodynamic Fragmentation
PSD	Particle Size Distribution
LDA	Laser Doppler anemometry
CFD	Computational Fluid Dynamics
GCC	Gravitational Classification Chamber
SOS	Sharpness of Separation
EU	European Union

Nomenclature

Symbol	Explanation
°F	Unit of temperature in ferenheit
°C	Unit of temperature in celcius
μm	Micrometer, unit of length
mm	Millimeter, unit of length
m/s	Meter per second, unit of velocity
Kg/m^3	Kilogram per cubic meter, unit of density
m^3/h	Cubic meter per hour, unit of mass flow rate

1 Introduction

The aim of this chapter is to:

- *Give a general introduction of refractory materials.*
- *Discuss thesis background and significance.*
- *Discuss thesis goal and objectives.*

1.1 General

Refractories are materials having a withstanding functionality at large temperatures for a sustainable period of time. It can sustain even in contact with corrosive gases and liquids. The raw substance of refractory materials is naturally produced from synthetic materials such as alumina, fireclays, bauxite, chromite, dolomite, etc [1]. Refractories were produced on a worldwide scale of 36.9 million tonnes in 2014, with China alone producing about two-thirds of this total. With 73% of the overall usage in 2013, the steel industry is by far the largest end-user consumer of refractories globally [2][3].

1.2 Thesis Background

Refractory products are used in the inner linings of furnaces, ladles, kilns, etc, of all elevated-temperature production processes such as cement, steel, and glass. The production process of refractory raw material is quite energy-intensive and mostly has the highest impact on the products' carbon footprint. The development of efficient recycling processes establishing circular economy routines for the refractory industry is therefore essential to reduce CO_2 emissions as well as preserve natural resources. In present practice, the fine fraction (particle size $<$ 5–10 mm) of the refractory waste is mostly used in landfilling since it is challenging to recover elements/components for using as secondary raw materials and downcycling applications. Fine refractory waste is considered powders/bulk solids, as their behavior is dominated by collective statistical characteristics rather than the properties of individual particles. Due to the complexity of fine particle behavior and strong particle-particle interactions, there are still many generic challenges in the field of powder sorting/classification/separation. The state-of-the-art of particle separation methods has not sufficiently developed to find efficient off-the-shelf solutions for fine refractory wastes. This also makes a negative impact on the establishment of circular economy routes in many other industries, hampering efficient valorization of various by-streams and wastes.

1.3 Thesis Signification

As already stated, refractory materials are discarded after serving their purpose. But over the past 20 years, the refractory industry has preferred recycling, minimizing environmental harm and lowering operational costs [4]. In a steel plant, about 4,100 tons of refractory refuse are produced each month. A part of refractory that is close to 40% can be saved and used again in the industry with an effective recycling procedure [4]. Keeping this in mind, the research will serve the following purposes:

- This research will help to reduce the harm that refractory waste does to the environment.
- This research will help to decrease the need to mine new raw resources for refractory materials.
- This research will help to reduce production and operating costs.

1.4 Thesis Objectives

The main objectives of this thesis are as follows:

- Literature study to recognize the powder sorting and classifying technologies.
- Laboratory experimental trials using the sample materials to develop direct & customized sorting methods.
- Draw conclusions based on the experiments.

1.5 Thesis Structure

This thesis has been structured as follows:

- Chapter 1 gives a general introduction and goals of this thesis.
- Chapter 2 gives an overview of the circular economy, studies related to refractory materials, and state of art of related technologies.
- Chapter 3 sheds light on the experimental procedure of this thesis.
- Chapter 4 discusses the results and outcomes of this thesis.
- Chapter 5 focuses on final conclusion and future works.

2 Literature Review

The aim of this chapter is to:

- *Give an overview of the circular economy.*
- *Discuss why the European Union takes the circular economy seriously.*
- *Discuss particle classification methods and technologies.*
- *Studies and research pertaining to materials sorting processes.*

2.1 What is Circular Economy?

Circular economy (CE), a paradigm that encourages more responsible patterns of production and consumption, has arisen during the past few decades. The over-exploitation of natural resources is a result of the increased development in global good consumption. Thus, the CE is a reaction to the need to integrate a system that emphasizes material reduction, reuse, recycling, and recovery across the production, distribution, and consuming processes in order to separate environmental pressure from economic development [5]. In actuality, it refers to minimizing waste. When a product reaches the end of its useful life, its components are wherever possible preserved within the economy. These may be productively applied repeatedly, adding more value [6]. Figure 2.1 shows an illustration of the circular economy model.

2.2 Initiatives Taken by EU on Circular Economy

The European Union and China are currently well along in the adoption of the circular economy model. In contrast, the European Union adopted its action plan for its implementation in 2015, while the latter passed a particular circular economy law in 2008 [5].

The circular economy action plan was unveiled by the European Commission in March 2020 with the goals of promoting more environmentally friendly product design, cutting waste, and empowering consumers (for instance, by establishing a right to repair). The

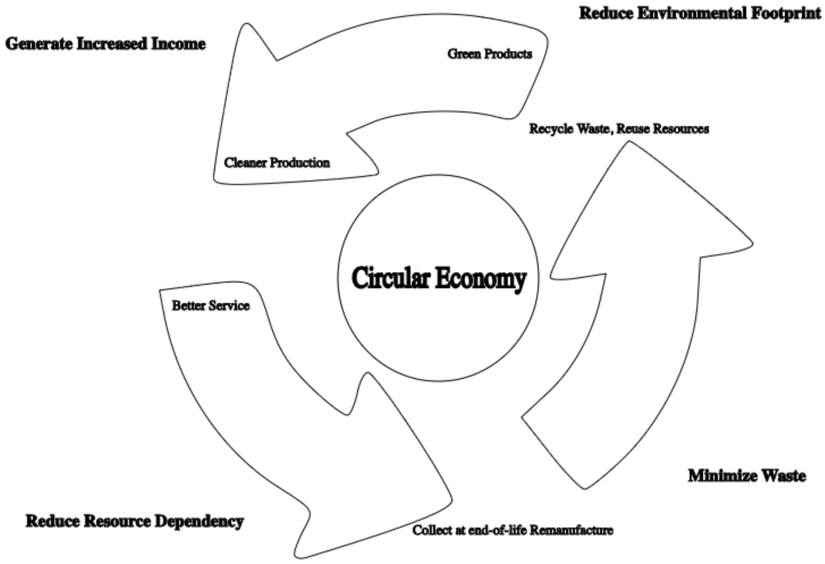

Figure 2.1: Circular Economy

emphasis is on industries that use a lot of resources, such as electronics and technology, plastics, textiles, and construction. A resolution on the new circular economy action plan was adopted by the Parliament in February 2021. It called for additional steps to be taken, such as stricter recycling regulations and binding targets for material use and consumption by 2030, in order to achieve a carbon-neutral, environmentally sustainable, toxic-free, and fully circular economy by 2050 [6].

2.3 Why Circular Economy is Important

Wastes are transformed into resources in a circular economy model so they may be recycled and used again. Through deliberate and interconnected production chains, the value of the resources that are created and exploited should be retained in circulation. The final use of the material is considered part of the design process for functional systems and products rather than a question of waste management [7].

The population of the globe is increasing along with the need for raw materials. Yet there is a limited quantity of necessary raw resources. The ecosystem is significantly impacted by the extraction and use of raw resources. Additionally, it raises CO_2 emissions and energy use. However, CO_2 emissions can be reduced by using raw resources more wisely.

Developing a more circular economy might positively affect the environment, increase raw material supply security, promote competitiveness, encourage innovation, accelerate economic growth, and generate employment. Additionally, consumers will receive items that are more inventive and long-lasting, improving their quality of life and long-term financial savings [6].

2.4 Concept of Recycling of Refractory Waste

Refractory industry products are essential for the manufacturing of heavy industrial goods including cement, aluminum, and glass, as well as steel and iron [8]. A lack of refractory materials, such as refractory bricks or refractory mixes, would make it impossible for corresponding companies to create their goods using heat processes. Due to the poor quality of the raw materials (regenerates) recovered from end-of-life materials, only a tiny portion of the refractory materials now in use can be recycled. Considering this, industrial recycling of refractory raw materials would decrease reliance, save resources, and lower world CO_2 emissions [8]. Refractory materials can be recycled using various techniques, each of which requires a number of processes. Some of the most common recycling process phases are sorting, sampling, spectrometer analysis, etc. The importance of those phases, technologies, and certain scientific research and initiatives based on the recycling of refractory materials waste are briefly reviewed in this literature review part for better understanding.

2.4.1 Refractory Materials

Refractories are materials having a ceramic basis that is resistant to abrasion, corrosion from acids and alkalis, exceptionally high heat, and other stresses [9].
These materials are employed in the linings of furnaces, kilns, incinerators, and reactors and are frequently subjected to conditions exceeding 1,000 °F (811 K; 538 °C) [10].
There are different kinds of such materials used in industries. Neutral refractories are employed in environments with either acidic or basic slag and atmosphere because they are chemically stable to both acids and bases. Examples of these materials that are often used include (i) Carbon graphite (most inert).(ii) Chromites (Cr_2O_3).(iii) Alumina [10].
Basic refractories are those that are resistant to alkaline slags, dust, and fumes at high temperatures but vulnerable to acid slag damage. Such materials are: (i) Magnesia (MgO) - caustic, sintered and fused magnesia. (ii) Dolomite (CaO*MgO) - sintered and fused dolomite. (iii) Chromite - the main part of chrome ore [10].

2.5 Theory

Materials sorting technologies have been discussed in this section.

2.5.1 Materials Sorting Techniques and Classifiers

There are a number of sorting and classification techniques that make use of various material characteristics, such as the material's surface's hydrophobic or hydrophilic characteristics or its electrical conductivity [11]. Traditionally two types of Classifiers are used such as dry and wet classifiers and the main difference is the medium of suspension [12]. For wet classifiers liquid is sued as a medium of suspension and for dry classifiers air or gas is used as a medium of suspension [12]. The majority of technological sorting techniques rely on material preparation. Reducing the material's size to a more appropriate shape is typically the initial step in the sorting process. Shredding, milling, and other techniques are used to achieve size reduction and fragmentation. Before the actual separation, the material can also be cleaned if the procedure calls for it. Sieving might also come before classification in a particular stage [11].

2.5.2 Automated Sorting

Direct sorting and indirect sorting are the two main categories of automated waste sorting methods [13]. Direct sorting techniques use external forces like magnetic, eddy current, and gravity to separate materials based on characteristics like electrical conductivity, density, etc. On the other hand, indirect sorting makes use of sensors, and mechanical, and automated devices to find recyclables in the waste and sort the items [13].
The REFRASORT European FP7 project seeks to provide an automated sorting technique to separate discarded refractory bricks into pure material fractions under industrial circumstances. The REFRASORT system combines a cutting-edge identification method based on LIBS (Laser Induced Breakdown Spectroscopy) with a mechanical handling device capable of handling huge and heavy items[14].

2.5.3 Manual Sorting

It is the simplest hand-sorting process that may be seen where materials can be divided into many groups. The simplest to arrange, although it is not the most productive or cost-effective [11]. Manual sorting might not be a viable solution for large-capacity recycling facilities [15].

2.5.4 Screening Sorting

The most common and traditional way of grouping objects according to size is unquestionably screening [11]. Various screens and sieves can be used to separate waste and a vibrating screen is the most typical screen used for screening dry bulk particles. Common names for this sort of screen are gyratory separator and vibrating screening machine[16].

2.5.5 Air-Gravity based sorting

Different densities are needed for the sorted particles in this dry sorting method. The air velocity is one of the most crucial operational factors for this sorting method. The fan's wind speed may be changed to alter the airflows. This method of sorting is utilized to remove light or small particles from the stream during the operation [11].

Cross-Flow Classifier

Airflows in cross-flow classifiers are oriented to face perpendicularly to gravity. The gas is pumped into the classifier horizontally from the intake on the left wall, as seen in Figure 2.2. The powders are fed downward into the classifier from the material input, which is close to the gas nozzle. In the chamber, the particles are arranged in a fan-like pattern. Due to fluid drag forces and gravity forces, the coarse and fine powders have distinct trajectories in the separation zone, which causes the particles to be separated. More quickly than fine particles, coarse powders settle. The separated particles are gathered into fractions by positioning the various plates in relation to the gas entrance at certain distances. They are frequently used to categorize particles by their densities rather than their sizes [12].

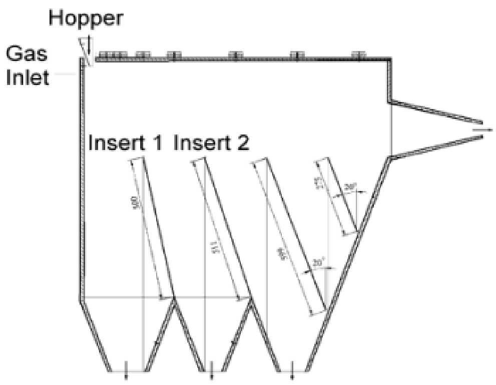

Figure 2.2: Cross-flow classifier [12]

Fluidized Bed Classifiers

In these systems, classification takes place above a fluidized bed where small particles are removed by the airflow. The airspeed must be significantly higher than the maximum fluidization speed of the fine fraction. Another advantage of this system is that coarse particles can flow horizontally over the bed to the exit. Fluidized bed classifiers come in both straight and elongating shapes. The latter, (Figure 2.3(a)) consists of a branch for a coarse product, inlet and outflow pipes, and a conical chamber with a grid permeable for particles fed from below. Because of the high air velocity in the openings, all the particles go upward and into the cone, where the stream expands and the particles slow down. The fine particles are transported away while the coarse material returns to the grid. Crushing is removed in a subsequent generation of fluidized bed classifiers because the feed is placed onto the grid from above (Figure 2.3(b), (c)). The formation of dead zones inside the fluidized bed far from the axis, where the particles do not flow, is a drawback of fluidized bed classifiers with cylindrical chambers of large diameters (above 1 m). These zones are eliminated by FB classifiers' oblong (oval) form chambers as in Figure 2.3(d) [17].

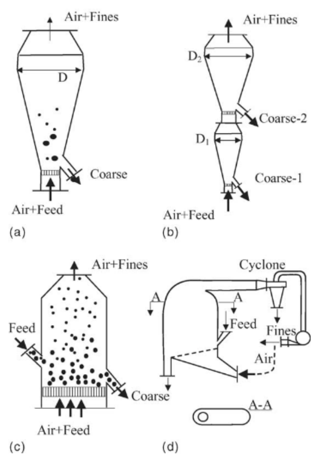

Figure 2.3: Fluidized bed classifiers [17]

Cascade Classifier

Shown in Figure 2.4, these devices often referred to as "zigzag classifiers," are zigzag-shaped vertical channels formed by cascades of numerous inclined branch pipes with rectangular cross sections. Particles supplied from above are swept up by air moving downward in a cross-current manner. There are vortices in the flow field inside the chamber at the turn points, where the stream drags the fines and the coarse particles cross it to flow down the opposite wall. When there is cross-flow, separation happens.

Multiple scavenging is made possible by the design of sequential pipes, which increases separation effectiveness [17].

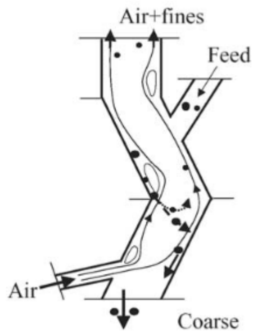

Figure 2.4: Cascade classifier [17]

Vortex Air Classifier

Centrifugal classifiers include vortex air classifiers in their category. Initially, this type of classifier was thoroughly researched by Rumphf [12]. These classifiers are produced by Alpine A-G based on Rumpf's innovations. One of these devices (Figure 2.5) is made to seem like a flat, horizontal cylinder with a vortex chamber within. Via inclined vanes, particle-filled air is introduced into the chamber, where it travels in a spiral motion, expelling the fines. The wall area is where coarse particles are pulled, and they depart through a screw outlet. These classifiers are used to separate fine powders, such as pigments, quartz, limestone, and others, with cut sizes ranging from 5 to 100 m. [17].

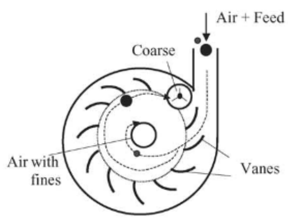

Figure 2.5: Vortex air classifier [17]

2.5.6 Electro-Magnetic Sorting

The method of selective separation known as magnetic separation makes use of the various driving forces that each particle is subjected to based on its magnetic properties. It is a potential technique to effectively separate magnetic particles. Conventionally, wet magnetic separation systems are employed, but they have drawbacks, including the need for drying after separation and trouble operating in cold climates. Therefore, magnetic separation using a dry procedure is a potential alternative technique [18].

Electrodynamic Fragmentation

Figure 2.6 illustrates the process. This technique uses pulsed power discharges that separate compound materials individually. It uses a Marx generator to produce a higher rate of high-voltage charges. Besides high voltage charges a high slew rate is important too for the process. EF is an innovative method that helps to separate multi-phase materials along grain boundaries. The discharge has to take place underwater to enable the penetration of solid materials. This whole process is also called the "wet process" for that reason [8].

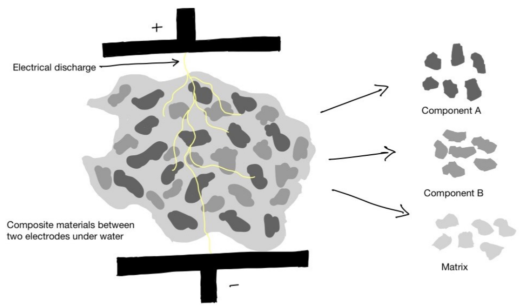

Figure 2.6: Electrodynamic fragmentation process

2.5.7 Particle Size Distribution (PSD)

The PSD is the abbreviation for particle size distribution. A sample of powder has a variety of sized particles. It is required to determine the population size of the particles and specify what percentage of the sample corresponds to each size in order to characterize the solids for specific applications where size is an important characteristic [19].

Particle Size Distribution Curve

The outcome of the analysis of the particle size distribution is presented as a curve known as the particle size distribution curve, where the cumulative percent of the material's finer portions—both coarse and fine-grained is expressed on the Y-axis and the size of a

particle is expressed on the X-axis on a log scale.
There are two methods to display a PSD curve. Particle size rises from left to right in one type of graph while decreasing from left to right in the other. Both representations are employed for practical purposes. When observing the PSD curve, it is important to pay close attention to the chosen horizontal scale [20].

Tromp Curve

The Tromp curve (Figure 2.7), also known as the separation curve is typically used to assess a separator's performance. Tromp curves are used to create a variety of features that enable comparisons between one generation of separators and others[21].
Numerous features of the Tromp curve are crucial for assessing the separation process. They are given numerical values by the Tromp curve: (Cut size value, Sharpness of separation)[21]
The cut size d_{50} corresponds to 50% of the feed going into the coarse stream. This size hence has an equal chance of crossing into coarse or fine streams [21].
The sharpness of separation is defined as follows [21]:

$$Sh = \frac{d_{75}}{d_{25}} \tag{2.1}$$

Where, Tromp values of 25% and 75% for the particle size d_{25} and d_{75}. An ideal separator has Sh of 1 [21].

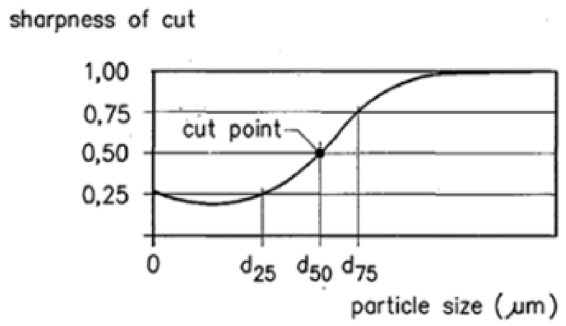

Figure 2.7: Tromp Curve for Sharpness of separation [21]

2.5.8 Imperfection Factor

The imperfection factor provides a great understanding of separator behavior according to the index shown in Figure 2.8. It can be used to compare different separators [21]. The formula is given below [21]:

$$I = \frac{d_{75} - d_{25}}{2 * d_{50}} \tag{2.2}$$

I < 0,2 Excellent separator	0,4 < I < 0,6 Poor separator
0,2 < I < 0,3 Good separator	0,6 < I < 0,7 Bad separator
0,3 < I < 0,4 Normal separator	I > 0,7 Execrable separator

Figure 2.8: Imperfection Factor Index[21]

2.6 Literature Study on Refractory Waste Materials

In this section, research and experiments related to different classifying methods and their performance analysis have been discussed. Some experiments related to the recycling of refractory waste materials have also been put up to understand the art of state of the powder technology processes.

2.6.1 Study related to the performance evaluation of classifiers

Q.Wang et al. [22] conducted an experimental investigation as well as a computational analysis of cross-flow air classifier performance. Fluent, a package for computational fluid dynamics (CFD), is utilized in the experiment. Using Laser Doppler anemometry (LDA), the classifier's flow fields were measured in a variety of setup scenarios and geometries. The patterns of behavior of separation parameters, such as cut size and sharpness of cut, have been examined under various boundary conditions using sieve analyses and the HELOS-laser technique. The purpose of this study is to determine the causes of performance that fall short of expectations as well as measures to enhance cut sharpness using computer simulation [22]. Glass spheres with a density of 2650 kg/m^3 and a size range of 50–1100 mm were utilized as the feed material. [22]. The findings showed that the flow field in these classifiers largely depends on their shape and influences the sharpness of the cut. The cut-size projections and the experimental data coincide quite well. The key factors affecting the classifier's performance are the vortex, particle-particle collisions, turbulence, and variations in intake velocities [22].

Wei- Hsiang Lai et al. [23] conducted an experiment with gravitational classification chambers to increase its accuracy and reduce drawbacks by coupling a high-quality closed-loop wind tunnel. Pb37 and Sn 63 were the testing materials for this experiment. After the experiment, GCC was successful in classifying Pb-Sn particles smaller than 200 micrometers. There were some reasons that affected the performance of the classifier during the experiment. One main reason was particle-particle collision due to the increase in feed rate decreasing the performance of the classifier. The same reason was also mentioned in the Q.wang et al experiment [22].

H. A Petit et al. [24] conducted an experiment to evaluate the effectiveness of a cross-flow air classifier in lowering dust levels in produced sands. The washing method has historically been used to address this issue. For this, air classification is being researched as a possible replacement for washing that doesn't include water. The evaluation was conducted using discrete element modeling (DEM) and computational fluid dynamics (CFD). Sand with a grain size of 0–3 and 0–6 were the two types chosen. 5, 10, and 15 m/s were the three intake velocities that were examined. According to the results, sand that meets the specifications for fine aggregates in concrete is produced when air classification of 0-3 sand is done at 5 m/s. According to air classification, 0-3 sand production rates at 5 m/s, manufactured sand produced is equivalent to 75% of the material injected which can be a further increase to 83%. If the classifier is redesigned to operate at speeds lower than 5 m/s and to prevent recirculation zones, the performance may be enhanced. Sand production is not within the acceptable ranges for fine aggregates when air classification is performed at inlet speeds of 10 and 15 m/s.

2.6.2 Study related to the recycling of refractory materials

Seifert et al. [8] discussed the Electrodynamic Fragmentation method for the recycling of ceramic waste materials. The method has been described briefly in Section 2.5.6. 3 different refractory wastes were investigated containing potential regenerates shown in Table 2.1. For the recycling process, the regenerated ZAC and bauxite were used in the refractory concrete(RC) and tabular alumina was used with tamped concrete(TC). In parallel both mixtures were produced using primary raw materials to be used as a reference sample for comparison. The result found that the workability of the freshly produced mixture was comparable with the reference product [8].

Ji-gao Li et al. [25] proposed the shaking table gravity separator to separate and reuse of refractory aggregate of zircon sand From shell waste. In this process, the zircon sand can be used as surface sand material, but also be processed into powder and other products [25]. The size of zircon sand in the used sand shell waste was found between the 80-120 mesh range. Two levels of magnetic separation were arranged during the gravity separation process to remove iron impurities[25]. After the experiment, it has been found that using the gravity separation process, zircon sand was separated successfully from shell waste[25]. The shape of the zircon sand was found good and $Zr(ZrSiO_4)$ content was

Table 2.1: Sample material used [8]

Sample	Material	Potential Regenerates
Material 1	Sintered brick for inlet chambers for rotary kilns	Bauxite, zirconia-alumina fused grain (ZAC).
Material 2	Corundum stone for aluminum melting furnace	White Corundum.
Material 3	Functional refractory ceramic from the steel industry Bauxite, zirconia-alumina fused grain (ZAC) White corundum	Tabular alumina, white corundum

found over 95wt% and Fe_2O_3 content was found to be below 0.3wt%, which is considered to be suitable for the production of castings and other applications[25].
Horckmans et al. [14] discussed an ongoing European FP7 project namely REFRASORT. The aim of the project is to develop an automated sorting technology that will separate waste refractory bricks into pure material fractions following industrial conditions. The project emphasizes 8 type of refractories that covers 95% of the refractories used in the steel industry [14]. The REFRASORT system combines a novel identification technique based on LIBS (Laser-induced breakdown spectroscopy) with a mechanical handling system able to deal with large and heavy objects [14]. Up to 8 different types of big, heavy particles could be separated using the automatic sorting machinery that was developed. The 8 types of refractories can be grouped into three main classes: magnesia-based, doloma- based and alumina-based shown in Table 2.2 [14].

Simon et al. conducted an experiment on chromium oxide and chromium oxide corundum refractories to enable the recycling of refractory materials by thermal treatment using arc furnace technology [26]. By creating mixed Cr_2O_3 and Al_2O_3 crystals, chromium oxide from used refractories was recycled (escolaite- corund). The Cr_2O_3 rich wastes and clay were melted in an arc furnace, and the resultant material was employed as a raw material for new refractories with strong resistance against corrosion [26].

Most of the studies found are mainly based on computational simulation of the process and analysis of the refractory waste classifying performance or chemical treatment of the waste materials to enable the recycling opportunity to establish circular economy routes. But nothing significant was found in lab-scale practical experiments to understand the performance of the classifiers. That's why this thesis focused on cross-flow air classifiers for running lab-scale practical tests using steel and cement refractory waste materials. The main focus of the thesis is to evaluate the performance of the classifiers in sorting the waste particles to recover fine fractions of refractory waste enhancing the circularity of the refractory industry.

Table 2.2: Properties of 8 types of refractories studied in REFRASORT [14]

Group	Type	Composition
MgO-based	Fired MgO	High MgO, no C, low CaO
	MgO-C with antioxidant	High MgO, 5 – 15 wt% C, low CaO, antioxidant 3%
	MgO-C without antioxidant	High MgO, 5 – 15 wt% C, low CaO, no antioxidant
Doloma- based	Fired doloma	High MgO, high CaO, no C
	Doloma carbon	High MgO, high CaO, 5-15 wt% C
Alumina- based	Fired bauxite	High Al, Al/Si 8/1, low CaO/MgO/C
	Fired andalusite	High Al, Al/Si 2/1, low CaO/MgO/C
	Fired chamotte	High Al, Al/Si 1/1, low CaO/MgO/C

3 Experimental Procedure

The aim of this chapter is to:

- *Give an overview of the experimental procedure.*
- *Discuss the material selection, quantities, and process specifications.*
- *Discuss classification processes and PSD.*

3.1 Refractory Material Selection

For the experiment refractory materials from the cement and steel industry have been used. The sample materials had five different particle size ranges such as 0-0.25mm, 0.25-0.5mm, 0.5-1mm, 1-3mm, and 3-5mm. The fixed amount of particles shown in Table 3.1 were collected from each size range and mixed together. A total of 500g of sample particles from cement and steel were used for the classifying procedure to imitate the industrial condition.

Table 3.1: Sample materials and proportions

Material	0 - 0.25mm	0.25 - 0.5mm	0.5 - 1mm	1 - 3mm	3 - 5mm
Cement	70g	25g	75g	235g	95g
Steel	80g	80g	90g	210g	40g

3.2 Particle Classification

The sample particles were first classified into three different categories such as coarse, mid, and fine particles using a cross-flow air classifier. A brief working process of the classifier has been discussed in section 2.5.5. The classifier was operated at three different air flowrate and velocities. The pressure of the system was kept at 1 bar and a barometer was used to control and set the air feed rate of the system. The particles were fed via a feeder at the top. They came across vertically with the airflow and get separated into three different categories which are collected at the bottom with plastic bags. Figure 3.1 illustrates the classifier.

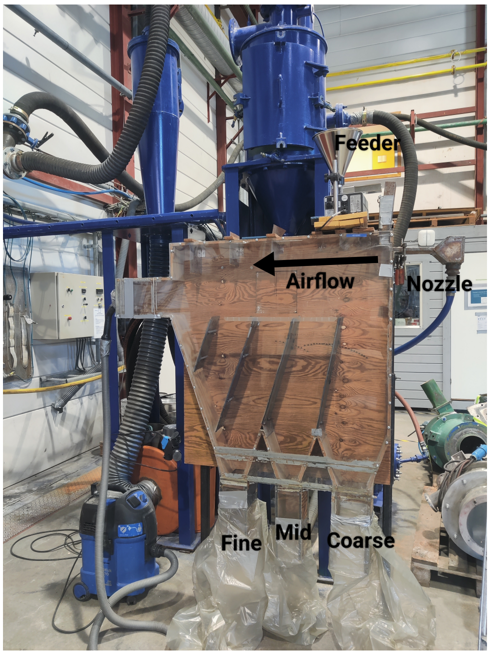

Figure 3.1: Crossflow Air Classifier

3.3 Classifier Air Speed

The sample materials were tested at 3 different air velocities 8 m/s, 12 m/s, and 14 m/s respectively. The air feed rates were 40 m^3/h, 60 m^3/h, and 70 m^3/h respectively for the corresponding velocities. The nozzle had 14 cm^2 of inlet area. The Air velocity is calculated as follows:

$$Q = A * V \tag{3.1}$$

Where Q is denoted as mass flow rate, A is the inlet area of the nozzle and V is velocity. Using Equation 3.1 the classifier air velocity can be calculated easily.

3.4 Sieving Process

By measuring the quantity of powder retained on a number of sieves with various-sized holes, sieve analysis is used to determine the particle size distribution of a solid substance. A sample is put on the top of a nest of sieves, which are organized from top to bottom in decreasing size. The material is divided into various-sized sieves as they vibrate. The particle size distribution and average sample diameter are then calculated using the weight of the sample retained on each sieve [27].

After separating the sample particles using a crossflow air classifier into 3 different size ranges such as coarse, mid, and fine, they were further classified using Sieves for PSD. A total of 14 different sizes of sieves including two bottom pans were used in this process. Two different sieve towers were made for precise PSD analysis. The sizes of the sieves are shown in Table 3.2.

Table 3.2: Sizes of sieves used for Sieve Towers

Sieve Tower 1	5.6mm	5mm	4mm	2.8mm	2mm	1.4mm	1mm	Pan
Sieve Tower 2	0.71mm	0.5mm	0.355mm	0.25mm	0.18mm	0.125mm	0.09mm	Pan

The amplitude of the sieve machines was kept at 1.5 mm/g with a 10-sec interval. Sieve machine 1 was sieved for 10 minutes and sieve machine 2 was sieved for 5 minutes. Figures 3.2 and 3.3 show the sieve machines used for the experiment.

3.5 Particle Size Distribution and Tromp Curve

The feed materials were classified into 3 samples: coarse, mid, and fine using the cross-flow air classifier. To calculate and generate PSD and tromp curve, each sample was further sieved in sieving towers. At first, the coarse particle sample was poured into sieving tower 1 and sieved for 10 minutes. After sieving, the remainder in the bottom pan of sieve tower 1 was again poured into sieve tower 2 for further sieving for 5 minutes. The weight of the sieves was measured twice when they were empty and after they were sieved. The same procedure was repeated for both mid and fine samples. Thus the values of particle size distribution on each sieve were calculated and further PSD curves and tromp curves were generated for the analysis of the performance of the classifier.

Figure 3.2: Sieve Machine 1

Figure 3.3: Sieve machine 2

4 Results & Discussion

The aim of this chapter is to:

- *Discuss the results of the experiment for case 1 and case 2.*
- *Discuss the results of the parameters such as sharpness of separation and imperfection factor.*

The experimental procedure was divided into two cases. In the first case, the classifying test was done at a wider size range of particles. The sample materials (Cement & Steel) of different class sizes were mixed together ranging from 0.25mm lowest to 5mm highest and classified using 3 different velocities (8, 12, 14 m/s) and feed rates (40, 60, 80 m^3/h). In the second case, the classifying test was done at the same velocity and feed rate but at a smaller size range of particles. Two different size ranges (0.5-1mm & 1-3mm) were chosen for both cement and steel samples to run the classifying test. The reason behind choosing this two size ranges for case 2 is not to end up with too many coarse materials or too many fine materials for the classifying procedure.

4.1 Case 1 Result for Cement

The test data table is given in Appendix A. The PSD curves and tromp curves are shown in Figures 4.1, 4.2, and, 4.3 respectively. The cross-flow classifier classified the feed materials into coarse, mid, and fine portions. Based on that Two tromp curves have been drawn to understand how much and what size of particles is going to the coarser and finer side. Tromp 1 basically gives an understanding of the coarse to coarse-mid-range separation performance of the classifier. Tromp 2 gives an understanding of the coarse-mid to finer range separation performance of the classifier. Combined it is possible to understand the whole separation process.

To determine the cut size value, d_{50}, and tromp parameters d_{25} and d_{75}, the linear interpolation method has been used to read the data from the graph. The calculated values from the graphs are shown in Tables 4.1, 4.2, and 4.3. The sharpness of separation was calculated using Equation 2.1.

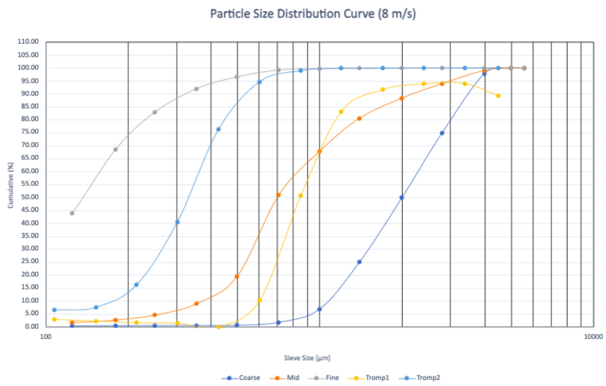

Figure 4.1: PSD and Tromp Curves at 8m/s

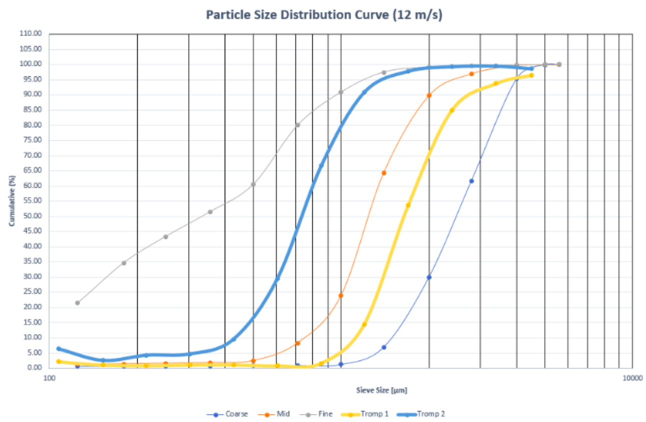

Figure 4.2: PSD and Tromp Curves at 12m/s

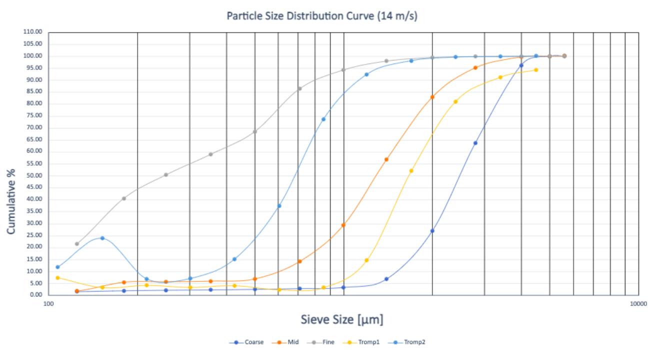

Figure 4.3: PSD and Tromp Curves at 14m/s

To have a perfect separation the value of sharpness of separation should be 1. In this case, from Table 4.1, the value came relatively greater than 1 for all the tests. That means particle size distribution is narrow.

d_{50} means that 50% of the total particles are smaller than this size or 50% of the particles

Table 4.1: Sharpness of separation values

Cement	**8 m/s**	**12 m/s**	**14 m/s**
SOS Tromp 1	1.54	1.63	1.63
SOS Tromp 2	1.68	1.73	1.71

Table 4.2: Tromp parameter values

Cement	**8 m/s**	**12 m/s**	**14 m/s**
d75 value Tromp 1	1080	2176	2190
d25 value Tromp 1	700	1334	1340
d75 value Tromp 2	420	973	870
d25 value Tromp 2	250	563	510

Table 4.3: Cut size values

Cement	**8 m/s**	**12 m/s**	**14 m/s**
d50 value Tromp 1	850	1750	1750
d50 value Tromp 2	340	740	690

are larger than this size. It is also known as median diameter. In this case for 8 m/s, the d_{50} value for tromp 1 is 850 microns from Table 4.3. That means 50% of particles are above 850 microns in diameter on the coarser side or 50% of particles below 850 microns in diameter on the coarse-mid side. d_{50} value obtained for tromp 2 is 340 microns. That means 50% of particles are below the diameter of 340 microns on the fine side or 50% above the diameter of 340 microns is in the coarse-mid side. For 12m/s and 14m/s the cut size value for tromp1 is same but different for Tromp 2.

4.2 Case 1 Result for Steel

The test data table is given in Appendix B. The PSD curves and tromp curves are shown in Figures 4.4, 4.5, and, 4.6 respectively.
The cut size value, d_{50}, and the tromp curve parameters, d_{25}, and d_{75}, for steel particles in this example were calculated using a methodology identical to that employed for cement in case 1. In Tables 4.4, 4.5, and 4.6, the estimated values from the graphs are shown. Using equation 2.1, the sharpness of separation was calculated.

In this case, the value came relatively greater than 1 for all the tests also. So particle size distribution is narrow for this case also.
In this case for 8 m/s, the d_{50} value for tromp 1 is 860 microns. That means 50% of particles are above 860 microns in diameter on the coarser side or 50% below to the

coarse-mid side. d_{50} value obtained for tromp 2 is 340 microns. That means 50% of particles are below the diameter of 360 microns on the fine side or 50% above the coarse-mid side. For 12m/s and 14m/s the d_{50} value came higher as expected.

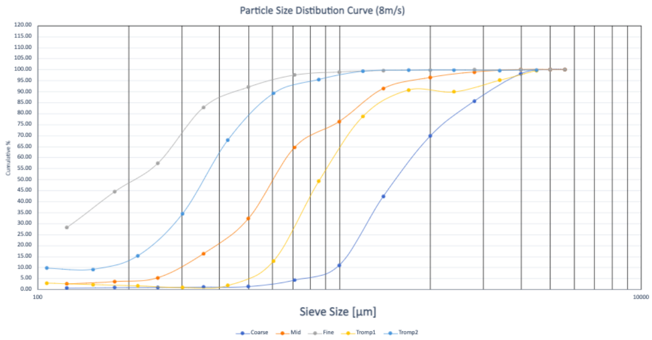

Figure 4.4: PSD and Tromp Curves at 8m/s

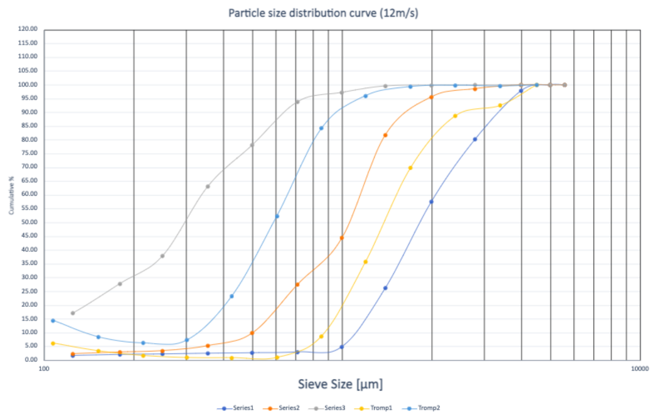

Figure 4.5: PSD and Tromp Curves at 12m/s

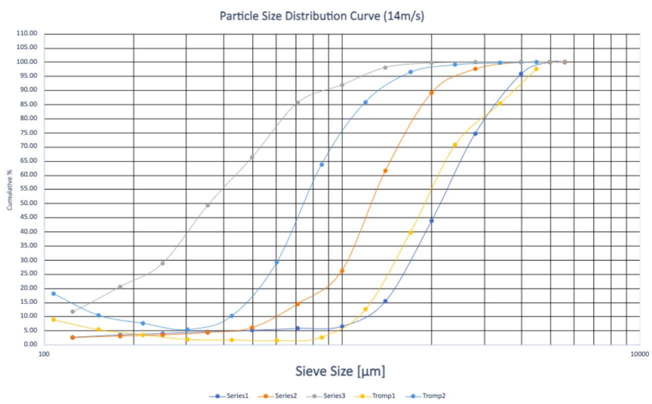

Figure 4.6: PSD and Tromp Curves at 14m/s

Table 4.4: Sharpness of separation values

Steel	**8 m/s**	**12 m/s**	**14 m/s**
SOS Tromp 1	1.64	1.70	1.82
SOS Tromp 2	1.81	1.73	1.74

Table 4.5: Tromp parameter values

Steel	**8 m/s**	**12 m/s**	**14 m/s**
d75 value Tromp 1	1130	1820	2600
d25 value Tromp 1	690	1070	1430
d75 value Tromp 2	470	760	990
d25 value Tromp 2	260	440	570

Table 4.6: Cut size values

Steel	**8 m/s**	**12 m/s**	**14 m/s**
d50 value Tromp 1	860	1400	1900
d50 value Tromp 2	360	590	750

4.3 Case 2 Result for Cement

For case 2, two different tests were done with two different size classes such as 1-3 mm and 0.5-1mm of particles of cement. Each of the size classes was tested at the same air velocity (8, 12, 14 m/s). Each of the size classes was tested for 500g of sample materials. The test data has been shown in Appendix C. The PSD curves and tromp curves for the size range 1-3mm are shown in Figures 4.7, 4.8, and 4.9 and the PSD curves and tromp curves for the size range 0.5-1mm are shown in Figures 4.10, 4.11, and 4.12 respectively.

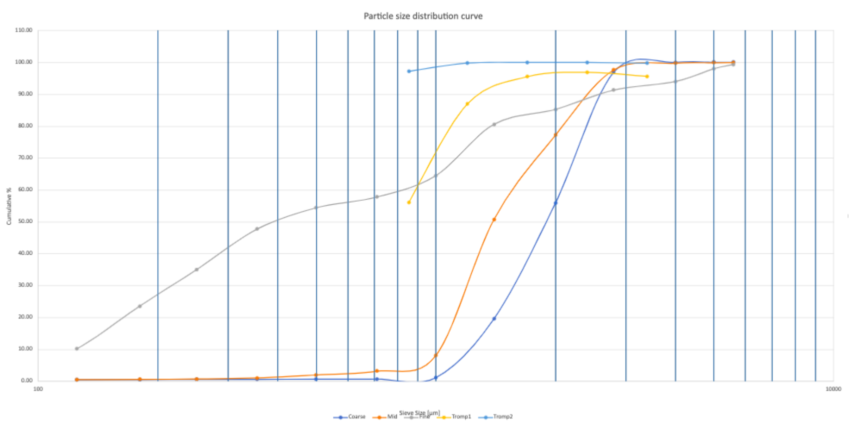

Figure 4.7: PSD and Tromp Curves 1-3mm at 8m/s

To determine the cut size value, d_{50}, and tromp curve parameters d_{25} and d_{75}, the linear

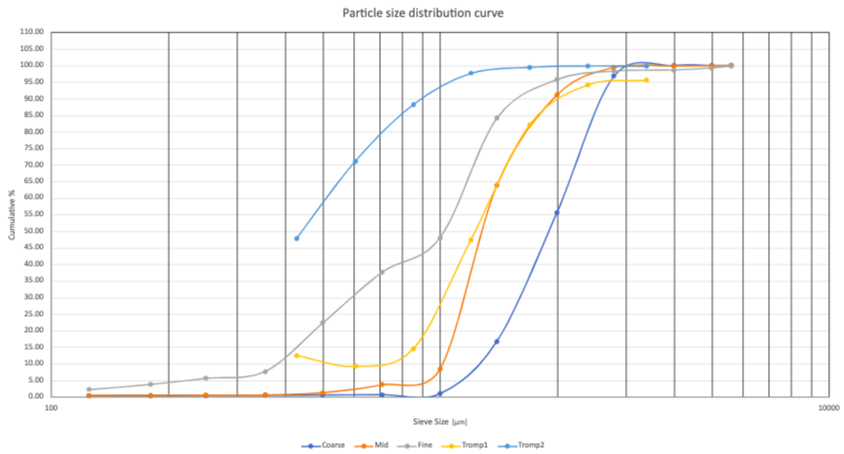

Figure 4.8: PSD and Tromp Curves 1-3mm at 12m/s

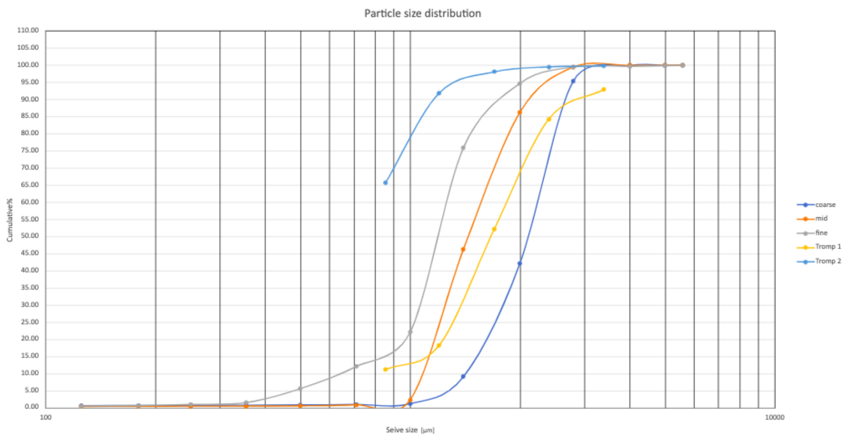

Figure 4.9: PSD and Tromp Curves 1-3mm at 14m/s

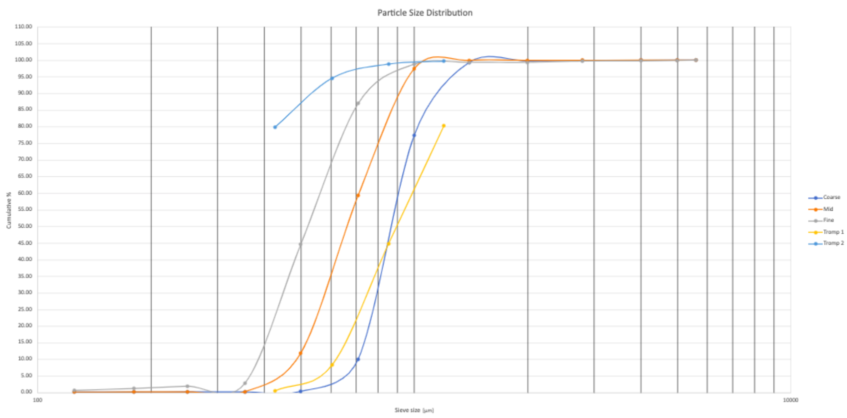

Figure 4.10: PSD and Tromp Curves 0.5-1mm at 8m/s

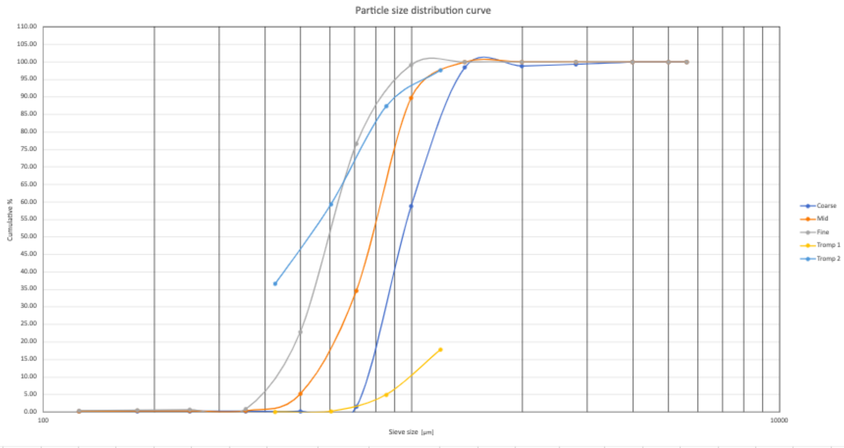

Figure 4.11: PSD and Tromp Curves 0.5-1mm at 12m/s

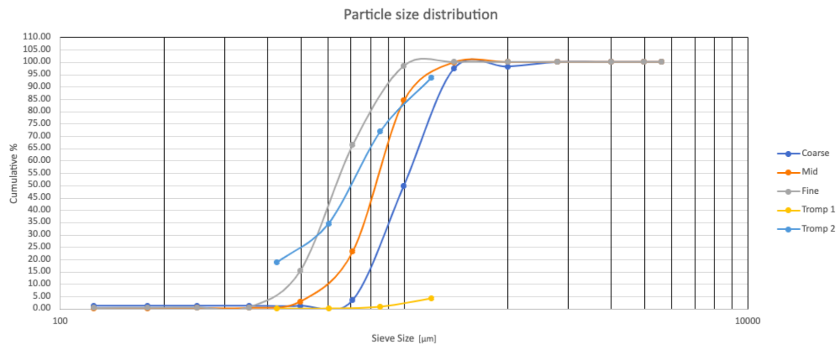

Figure 4.12: PSD and Tromp Curves 0.5-1mm at 14m/s

interpolation method has been used to read the data. The calculated values from the graphs are shown in Tables 4.7, 4.8, and 4.9 for the 1-3mm size range and Tables 4.10, 4.11, and 4.12 for the 0.5-1mm size range. The sharpness of separation was calculated using equation 2.1.

Table 4.7: Sharpness of separation values for 1-3mm size range

Cement	**8 m/s**	**12 m/s**	**14 m/s**
SOS Tromp 1	-	1.69	1.57
SOS Tromp 2	-	-	-

In Table 4.7, For 8m/s, the sharpness of separation can not be obtained. That is because 93% (see Index C) of the materials ended at the coarser portion during the classifying test. Rest was mid and fine particles. Due to that, there was no cut size (d_{50}) for this test because most of the particles are coarse particles. At 12m/s, the sharpness of separation is 1.69 for tromp 1 which indicates the narrow distribution of particles. For tromp 2 there

Table 4.8: Tromp parameter values for 1-3mm size range

Cement	8 m/s	12 m/s	14 m/s
d75 value Tromp 1	1050	1650	2200
d25 value Tromp 1	-	975	1400
d75 value Tromp 2	-	650	960
d25 value Tromp 2	-	-	-

Table 4.9: Cut size values for 1-3mm size range

Cement	8 m/s	12 m/s	14 m/s
d50 value Tromp 1	-	1300	1700
d50 value Tromp 2	-	450	-

was no sharpness of separation because for this run only 1.69% particles ended at a finer portion. The cut size value d_{50} for tromp1 at 12m/s is 1300 microns. That means 50% of particles are above 1300 microns in diameter on the coarser side. d_{50} value obtained for tromp 2 is 450 microns. That means 50% of particles are below the diameter of 450 microns on the finer side. For 14m/s, the sharpness of separation is 1.57 and d_{50} is 1700 microns for tromp1. That means 50% of particles are above 1700 microns in diameter on the coarser side. For tromp 2 cut size value can not be obtained because particles were very less on the finer side and were above d_{25}.

Table 4.10: Sharpness of separation values for 0.5-1mm size range

Cement	8 m/s	12 m/s	14 m/s
SOS Tromp 1	1.66	-	-
SOS Tromp 2	-	-	1.75

Table 4.11: Tromp parameter values for 0.5-1mm size range

Cement	8 m/s	12 m/s	14 m/s
d75 value Tromp 1	1200	-	-
d25 value Tromp 1	725	-	-
d75 value Tromp 2	-	740	890
d25 value Tromp 2	-	-	510

Table 4.12: Cut size values for 0.5-1mm size range

Cement	8 m/s	12 m/s	14 m/s
d50 value Tromp 1	900	-	-
d50 value Tromp 2	-	540	700

For 8m/s, from Table 4.10, the sharpness of separation value for tromp1 is 1.66. For tromp 2, it can not be obtained. Because from Index C it is seen most of the particles went to coarse and mid portions. A very little portion is separated into fine portions. For that reason, d_{50} value can not be obtained for tromp 2. For tromp 1, d_{50} value is 900 microns. That means 50% of particles above the diameter of 900 microns are distributed to the coarse side and 50% of particles lower than the diameter of 900 microns are distributed to the coarse-mid side. For 12m/s SOS can not be obtained because most of the particles were in the middle side. d_{50} value of tromp 2 indicates that 50% of particles lower than the diameter of 540 microns is distributed to the finer side and 50% above to the mid-coarse side. For 14m/s, the sharpness of separation for tromp 2 is 1.75 and d_{50} is 700. There were very few particles distributed to the coarse portions. That's why the sharpness of separation can not be obtained for tromp 1 .

4.4 Case 2 Result for Steel

For case 2, two different tests were done with two different size classes such as 1-3 mm and 0.5-1mm of particles of steel. Each of the size classes was tested at the same air velocity (8, 12, 14 m/s). Each of the size classes was tested for 500g of sample materials.
The test data has been shown in Appendix D. The PSD curves and tromp curves for the size range 0.5-1mm are shown in Figures 4.13, 4.14, 4.15 and the PSD curves and tromp curves for the size range 1-3mm are shown in Figures 4.16, 4.17, 4.18 respectively.

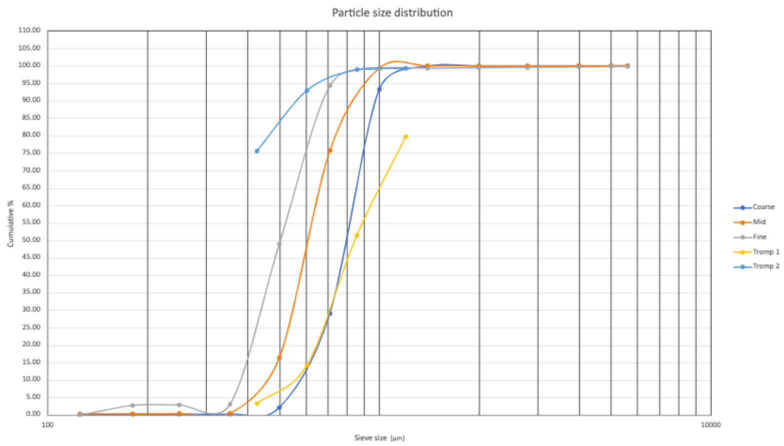

Figure 4.13: PSD and Tromp Curves 0.5-1mm at 8m/s

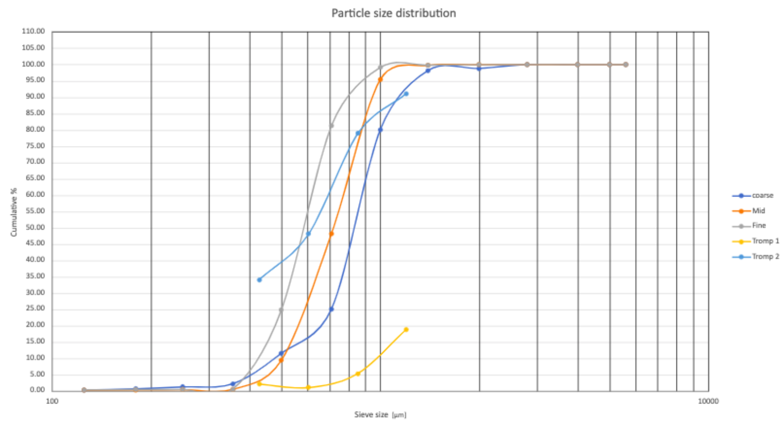

Figure 4.14: PSD and Tromp Curves 0.5-1mm at 12m/s

To determine the cut size value d_{50}, and Tromp curve parameters d_{25} and d_{75}, the linear interpolation method has been used to read the data from the graph. The calculated values from the graphs are shown in Tables 4.13, 4.14, and 4.15 for the 0.5-1mm size range and Tables 4.16, 4.17, and 4.18 for the 1-3mm size range. The sharpness of separation

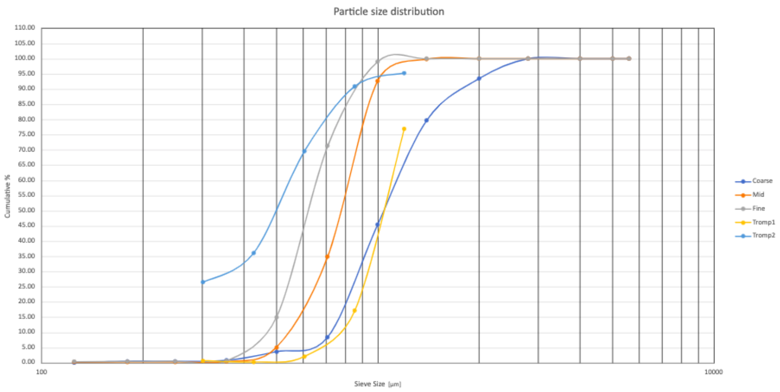

Figure 4.15: PSD and Tromp Curves 0.5-1mm at 14m/s

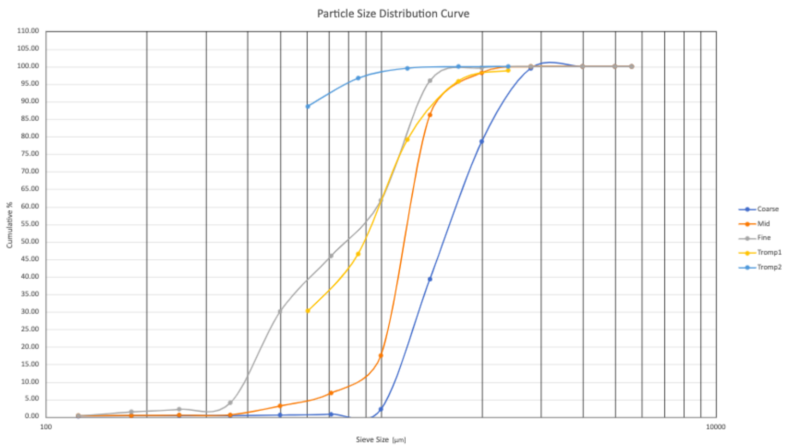

Figure 4.16: PSD and Tromp Curves 1-3mm at 8m/s

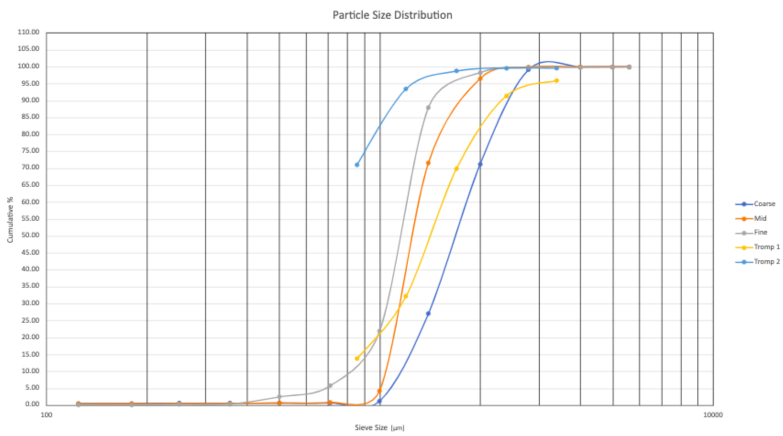

Figure 4.17: PSD and Tromp Curves 1-3mm at 12m/s

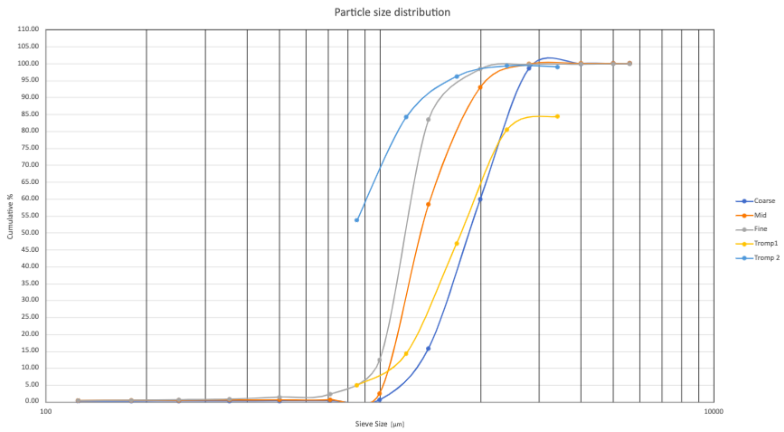

Figure 4.18: PSD and Tromp Curves 1-3mm at 14m/s

was calculated using equation 2.1.

Table 4.13: Sharpness of separation values for 0.5-1mm size range

Steel	**8 m/s**	**12 m/s**	**14 m/s**
SOS Tromp 1	1.78	-	1.37
SOS Tromp 2	-	-	-

Table 4.14: Tromp parameter values for 0.5-1mm size range

Steel	**8 m/s**	**12 m/s**	**14 m/s**
d75 value Tromp 1	1200	-	1250
d25 value Tromp 1	675	-	910
d75 value Tromp 2	-	800	650
d25 value Tromp 2	-	-	-

Table 4.15: Cut size values for 0.5-1mm size range

Steel	**8 m/s**	**12 m/s**	**14 m/s**
d50 value Tromp 1	850	-	1050
d50 value Tromp 2	-	625	500

Table 4.16: Sharpness of separation values for 1-3mm size range

Steel	**8 m/s**	**12 m/s**	**14 m/s**
SOS Tromp 1	-	1.68	1.59
SOS Tromp 2	-	-	-

Table 4.17: Tromp parameter values for 1-3mm size range

Steel	**8 m/s**	**12 m/s**	**14 m/s**
d75 value Tromp 1	1200	1850	2300
d25 value Tromp 1	-	1100	1450
d75 value Tromp 2	-	900	1100
d25 value Tromp 2	-	-	-

Table 4.18: Cut size values for 1-3mm size range

Steel	**8 m/s**	**12 m/s**	**14 m/s**
d50 value Tromp 1	900	1500	1800
d50 value Tromp 2	0	0	0

In Table 4.13, For 8m/s, the sharpness of separation for tromp 1 is 1.78, and for tromp2 it can not be obtained because only 7% particles went to the finer portion (see Index D). Due to that, no cut size was found for tromp2 and the cut size d_{50} for tromp1 is 850 microns. That means 50% of particles are above 850 microns in diameter and distributed to the coarser side. At 12m/s, the sharpness of separation for both tromp 1 and tromp 2 can not be obtained. That is because only 3.5% particles ended at the coarser side. So d_{75} and d_{25} values could not be obtained for tromp 1. Hence no cut size value. For tromp 2 particle distributions were mainly at the coarser and middle portion. For this reason, d_{25} can not be obtained hence no SOS can not be calculated. The cut size value for tromp2 d_{50} is 625 microns. That means 50% of particles are above 625 microns in diameter on the coarser side. For 14m/s the SOS value came best in this case which is 1.37 relatively closer to the ideal value of 1.

For 8m/s, from Table 4.16, the sharpness of separation tromp1 and tromp 2 can not be obtained. That is because from Appendix D it is seen that about 87% particles went to coarse portions. The very little portion is separated into fine and mid portions. For tromp 1, d_{50} value is 900 microns. That means 50% of particles above the diameter of 900 microns are distributed to the coarse side and 50% of particles lower than the diameter of 900 microns are distributed to the coarse-mid side. For 12m/s, SOS was found at 1.68 for tromp1 and could not be obtained for tromp 2 because most of the particles were in the coarse-mid sides. d50 value of tromp 1 indicates that 50% of particles above 1500 microns are distributed to the coarser side and 50% below to the mid-coarser side. For 14m/s, the sharpness of separation for tromp 1 is 1.59 d_{50} is 1800.

4.5 Imperfection Factor Result

The imperfection factor for both case 1 and case 2 has been shown in tables 4.19 and 4.20

Table 4.19: Imperfection Factors for the Cement case 1

Cement	**8 m/s**	**12 m/s**	**14 m/s**
Imperfection factor for Tromp 1	0.22	0.24	0.24
Imperfection factor for Tromp 2	0.25	0.27	0.26

Table 4.20: Imperfection Factors for the Steel case 1

Steel	**8 m/s**	**12 m/s**	**14 m/s**
Imperfection factor for Tromp 1	0.25	0.26	0.31
Imperfection factor for Tromp 2	0.29	0.27	0.28

From Tables 4.19 and 4.20, it can be seen that the imperfection factor value is mostly between 0.2 and 0.3 for both cement and steel case 1. According to section 2.5.8, this result indicates the good performance of the separator.

Table 4.21: Imperfection Factors for the Cement case 2 (1-3mm)

Cement	**8 m/s**	**12 m/s**	**14 m/s**
Imperfection factor for Tromp 1	-	0.26	0.23
Imperfection factor for Tromp 2	-	-	-

Table 4.22: Imperfection Factors for the Steel case 2 (1-3mm)

Steel	**8 m/s**	**12 m/s**	**14 m/s**
Imperfection factor for Tromp 1	-	0.25	0.23
Imperfection factor for Tromp 2	-	-	-

From Tables 4.21 and 4.22, it can be seen that the imperfection factor value is between 0.2 and 0.3 for both cement and steel case 2 for 12m/s and 14m/s respectively. which indicates the good separation in this range. For 8m/s imperfection factor can not be calculated due to the particles being heavily distributed to the coarser portion.

Table 4.23: Imperfection Factors for the Cement case 2 (0.5-1mm)

Cement	**8 m/s**	**12 m/s**	**14 m/s**
Imperfection factor for Tromp 1	0.26	-	-
Imperfection factor for Tromp 2	-	-	0.27

Table 4.24: Imperfection Factors for the Steel case 2 (0.5-1mm)

Steel	**8 m/s**	**12 m/s**	**14 m/s**
Imperfection factor for Tromp 1	0.30	-	0.16
Imperfection factor for Tromp 2	-	-	-

From Table 4.23, it can be seen that the imperfection factor value is between 0.2 and 0.3 for 8m/s and 14m/s in case 2. Which indicates a good separation. For 12m/s imperfection factor can not be calculated due to the particles being heavily distributed to the middle portion.

From Table 4.24, it can be seen that the imperfection factor value is between 0.2 and 0.3 for 8m/s in case 2 (0.5-1mm steel) which indicates a good separation. For 12m/s and 14m/s imperfection factor can not be calculated due to the particles distributed less to the coarser portions. At 14m/s the result indicates very good separation.

5 Concluding Remarks

The aim of this chapter is to:

- *Give a final overview of the experimental results.*
- *Discuss shortcomings and limitations*
- *Discuss future work and recommendations.*

5.1 Conclusion

From the results, it is seen that in case 1 for both cement and steel, the separation of sharpness and imperfection factor results came quite satisfactory for three different air velocities.

For 8m/s the classifier performance has been good according to the SOS value which is 1.54 and 1.68 for tromp 1 and tromp 2 respectively for cement compared to 12 m/s and 14m/s tests. Both 12m/s and 14m/s showed identical SOS values for cement. The cut size value increased with the increase of air velocity for cement. On the other hand for 12m/s the classifier performance has been good for steel according to the value of SOS which is 1.70 and 1.73 for tromp 1 and tromp 2 respectively compared to 8 m/s and 14m/s. The classifier showed variance in performance at different air velocities. With the increase in the velocity the cut size value also increased in this case.

The imperfection factor for both cement and steel in case 1 showed good performance of the separator. For all three different velocities, the results were between the 0.2 to 0.3 range which indicates the classifier is a good separator.

In case 2 (1-3mm) for both cement and steel at 8m/s, no sharpness of separation value was obtained. That's because in both tests particles were heavily distributed to the coarser side. For both 12m/s and 14m/s SOS values were obtained only for tromp 1. At 12m/s SOS value for cement is 1.69 and for steel 1.68 which is quite identical. At 14m/s SOS value for cement is 1.57 and for steel 1.59. For tromp 2 these values can not be obtained by having fewer particles distributed to the finer side. The cut size value increased with the increase in air velocity. On the other hand, for the 0.5-1mm size range, the SOS was found at 8m/s and 14m/s. For 12m/s no SOS value was obtained because particles were mostly distributed to the middle portion. The cut size value was higher at 8m/s and lowest at 12m/s.

The imperfection factor in case 2 for both cement and steel at a size range of 1-3mm showed identical results compared to the results at a size range of 0.5-1mm.

Finally, it can be concluded that for case 1, when five different size ranges (0.25mm being the lowest and 5mm being the highest) were used, the classifier's classification performance has been satisfactory. The sharpness of the separation and imperfection factor index indicates good performance. When the size range has been narrowed down to 1-3mm size range, the performance was good in some tests but when the size range was narrowed down to the range of 0.5-1mm the classifier performance went down. This can happen due to several reasons. One reason can be the effect of air velocity. The particles are relatively small at 1 to 3mm and 0.5 to 1mm ranges. When the air velocity is varied, the particle-particle collision may change the momentum of the flowing particles and also their trajectories. Another reason can be the influence of vortex and turbulence on smaller particles that can affect the trajectory of the particles and hence affect the classifier's performance. That's why the particles were heavily distributed either at coarser portions or at finer portions for these two range.

5.2 Future Works and Recommendation

Time has been a limiting factor for this thesis to experiment and study further for the improvement of the classifier's performance. Some future works and recommendations are given below:

- Test the same experiment with different classifiers such as fluidized bed classifiers to evaluate the performance of the cross-flow air classifier.
- Computational simulations can be used to understand the effect of turbulence and vortex on particle trajectories inside the classifier to improve the performance.
- Some parameters such as air velocity, and feed rate, etc can be varied for the experiments to evaluate the separator performance.
- In order to assess the enrichment of various components in the refractory waste and use them as feedstock or raw materials, more work, such as chemical analysis, should be done.

Bibliography

[1] The Refractories Institute, *What are refractories?* https://www.refractoriesinstitute.org/tri-pages/tri-what-are-refractories.asp, [Online; accessed 19-March-2023].

[2] I. Muñoz, A. Soto, D. Maza and F. Bayón, 'Life cycle assessment of refractory waste management in a spanish steel works,' *Waste Management*, vol. 111, pp. 1–9, 2020.

[3] G. Simandl, S. Paradis and P. Luck, *Refractory minerals in british columbia, canada, 2014*, Jan. 2014.

[4] Glasstech Refractory, *The importance of recycling of refractory materials*, http://www.glasstechrefractory.com/faq/the-importance-of-recycling-of-refractory-materials, [Online; accessed 19-March-2023], 2021.

[5] M. Negrete-Cardoso, G. Rosano-Ortega, E. L. Álvarez-Aros, M. E. Tavera-Cortés, C. A. Vega-Lebrún and F. J. Sánchez-Ruíz, 'Circular economy strategy and waste management: A bibliometric analysis in its contribution to sustainable development, toward a post-covid-19 era,' *Environmental Science and Pollution Research*, vol. 29, no. 41, pp. 61 729–61 746, 2022.

[6] News, European Parliament, *Circular economy: Definition, importance and benefits*, https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits, [Online; accessed 15-February-2023], 2015.

[7] S. Sehnem, D. Vazquez-Brust, S. C. F. Pereira and L. M. Campos, 'Circular economy: Benefits, impacts and overlapping,' *Supply Chain Management: An International Journal*, vol. 24, no. 6, pp. 784–804, 2019.

[8] S. Seifert, S. Dittrich and J. Bach, 'Recovery of raw materials from ceramic waste materials for the refractory industry,' *Processes*, vol. 9, no. 2, p. 228, 2021.

[9] R. Waghela, S. Parmar, S. Vasava and D. N. Mehta, 'Review of refractory materials for innovative investigation and testing,' *International Journal of Advance Engineering and Research Development, e-ISSN (O)*, pp. 2348–4470, 2018.

[10] K. Magesh, N. Pappayee and K. Santhosh, 'Reduce, reuse and recycling technology for refractories in cement industries,' *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 5, no. 6, 2016.

[11] V. Lahtela and T. Kärki, 'Mechanical sorting processing of waste material before composite manufacturing-a review.,' *Journal of Engineering Science & Technology Review*, vol. 11, no. 6, 2018.

[12] W. Yang, *Particle separation and classification*, Apr. 2007. DOI: 10.13140/RG.2.1.4440.9844.

[13] S. P. Gundupalli, S. Hait and A. Thakur, 'A review on automated sorting of source-separated municipal solid waste for recycling,' *Waste management*, vol. 60, pp. 56–74, 2017.

[14] L. Horckmans, H. Knapp, P. Dierckx *et al.*, 'Refrasort: Automated sorting of refractory waste for high value recycling,' *Proceedings of the 7th Sensor-Based Sorting & Control*, 2016.

[15] D. A. Wahab, A. Hussain, E. Scavino, M. Mustafa and H. Basri, 'Development of a prototype automated sorting system for plastic recycling,' *American Journal of Applied Sciences*, vol. 3, no. 7, pp. 1924–1928, 2006.

[16] Bulkinside, *Innovations in screening and separation in dry material handling operations*, https://bulkinside.com/bulk-solids-handling/screening-separation/, [Online; accessed 5-March-2023].

[17] M. Shapiro and V. Galperin, 'Air classification of solid particles: A review,' *Chemical Engineering and Processing: Process Intensification*, vol. 44, no. 2, pp. 279–285, 2005.

[18] Y. Nakai, F. Mishima, Y. Akiyama and S. Nishijima, 'Development of magnetic separation system for powder separation,' *IEEE Transactions on applied superconductivity*, vol. 20, no. 3, pp. 941–944, 2010.

[19] PowderProcess, *Particle size distribution (psd)*, https://powderprocess.net/psd.html, [Online; accessed 5-March-2023].

[20] Elementary Engineering Library, *Particle size distribution curve*, https://www.elementaryengineeringlibrary.com/civil-engineering/soil-mechanics/particle-size-distribution-curve, [Online; accessed 19-March-2023], 2019.

[21] T. Belhaj, M. Higazy, A. Gaafer and B. ELMogy, 'Improvement of productivity using tromp curve measurement for cement separator processing technology,' *Scientific Journal of October 6 University*, vol. 3, no. 2, pp. 35–44, 2016.

[22] Q. Wang, M. C. Melaaen and S. R. De Silva, 'Investigation and simulation of a cross-flow air classifier,' *Powder Technology*, vol. 120, no. 3, pp. 273–280, 2001.

[23] W.-H. Lai, W.-F. Lu and M.-C. Chou, 'Sorting of fine powder by gravitational classification chambers,' *Advanced Powder Technology*, vol. 20, no. 2, pp. 177–184, 2009.

[24] H. Petit, E. F. Irassar and M. R. Barbosa, 'Evaluation of the performance of the cross-flow air classifier in manufactured sand processing via cfd–dem simulations,' *Computational Particle Mechanics*, vol. 5, no. 1, pp. 87–102, 2018.

[25] J.-g. Li, Y.-c. Li and S.-m. Tan, 'Experimental study on separation of valuable refractory aggregate from investment casting ceramic shell waste,' *China Foundry*, vol. 13, pp. 243–247, 2016.

[26] F.-G. Simon, B. Adamczyk and G. Kley, 'Refractory materials from waste,' *Materials transactions*, vol. 44, no. 7, pp. 1251–1254, 2003.

[27] K. Dishman, 'Sieving in particle size analysis,' in Sep. 2006, ISBN: 0471976709. DOI: 10.1002/9780470027318.a1514.

Appendix A

PSD Data Table of Cement Sample Case 1

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.5	559.52	559.52	559.52	0.02	0.02	0.02	0.06	0.012	33.33	33.33	33.33
5000	576.71	576.72	576.72	576.71	0.01	0.01	0	0.02	0.004	50.00	50.00	0.00
4000	549.42	556.43	550.26	549.42	7.01	0.84	0	7.85	1.621	89.30	10.70	0.00
2800	552.75	626.73	557.5	552.75	73.98	4.75	0	78.73	16.261	93.97	6.03	0.00
2000	333.4	413.89	338.62	333.4	80.49	5.22	0	85.71	17.702	93.91	6.09	0.00
1400	387.04	467.25	394.29	387.13	80.21	7.25	0.09	87.55	18.082	91.62	8.28	0.10
1000	363.15	421.74	375.02	363.24	58.59	11.87	0.09	70.55	14.571	83.05	16.82	0.13
Pan	394.72	416.83	457.86	463.17	22.11	63.14	68.45					
710	501.95	518.49	517.72	502.3	16.54	15.77	0.35	32.66	6.746	50.64	48.29	1.07
500	493.35	496.91	522.58	495.18	3.56	29.23	1.83	34.62	7.150	10.28	84.43	5.29
355	463.6	463.85	473.47	466.76	0.25	9.87	3.16	13.28	2.743	1.88	74.32	23.80
250	254.68	254.82	258.78	260.91	0.14	4.1	6.23	10.47	2.162	1.34	39.16	59.50
180	286.64	286.83	288.37	296.5	0.19	1.73	9.86	11.78	2.433	1.61	14.69	83.70
125	243.24	243.64	244.21	260.16	0.4	0.97	16.92	18.29	3.778	2.19	5.30	92.51
90	389.8	390.18	390.28	402.12	0.38	0.48	12.32	13.18	2.722	2.88	3.64	93.47
Pan	345	345.79	345.92	362.77	0.79	0.92	17.77	19.48	4.023	4.06	4.72	91.22
SUM					322.42	93.1	68.65	**484.17**				

% of diff particles in total	
Coarse [g]	66.6
Mid [g]	19.2
Fine [g]	14.2

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.01	0.02	0.00
	5000	0.00	0.01	0.00
	4000	2.17	0.90	0.00
	2800	22.95	5.10	0.00
	2000	24.96	5.61	0.00
	1400	24.88	7.79	0.13
	1000	18.17	12.75	0.13
	710	5.13	16.94	0.51
	500	1.10	31.40	2.67
	355	0.08	10.60	4.60
	250	0.04	4.40	9.08
	180	0.06	1.86	14.36
	125	0.12	1.04	24.65
	90	0.12	0.52	17.95
Pan	0	0.25	0.99	25.88

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
99.99	99.98	100.00
99.99	99.97	100.00
97.82	99.07	100.00
74.87	93.96	100.00
49.91	88.36	100.00
25.03	80.57	99.87
6.86	67.82	99.74
1.73	50.88	99.23
0.62	19.48	96.56
0.55	8.88	91.96
0.50	4.48	82.88
0.44	2.62	68.52
0.32	1.58	43.87
0.20	1.06	25.93
-0.04	0.08	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500	89.3	100.00
3400	93.97	100.00
2400	93.91	100.00
1700	91.62	99.90
1200	83.05	99.87
855	50.64	98.93
605	10.28	94.71
427.5	1.88	76.20
302.5	1.34	40.50
215	1.61	16.30
152.5	2.19	7.49
107.5	2.88	6.53

Figure A.1: PSD data table of cement sample for speed 8m/s

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.51	559.54	559.51	559.51	0.03	0	0	0.03	0.006	100.00	0.000	0.000
5000	576.75	576.92	576.75	576.78	0.17	0	0.03	0.2	0.041	85.00	0.000	15.000
4000	549.41	559.2	549.63	549.54	9.79	0.22	0.13	10.14	2.075	96.55	2.170	1.282
2800	552.62	624.51	557.09	552.94	71.89	4.47	0.32	76.68	15.691	93.75	5.829	0.417
2000	333.19	401.29	344.72	333.67	68.1	11.53	0.48	80.11	16.392	85.01	14.393	0.599
1400	560.91	610.05	601.32	562.84	49.14	40.41	1.93	91.48	18.719	53.72	44.174	2.110
1000	362.92	375.06	427.12	370.56	12.14	64.2	7.64	83.98	17.184	14.46	76.447	9.097
Pan	344.98	347.59	382.9	450.45	2.61	37.92	105.47					
710	502.08	502.72	526.83	514.74	0.64	24.75	12.66	38.05	7.786	1.68	65.046	33.272
500	493.6	493.87	502.86	516.26	0.27	9.26	22.66	32.19	6.587	0.84	28.767	70.395
355	463.68	463.81	464.66	474.14	0.13	0.98	10.46	11.57	2.368	1.12	8.470	90.406
250	254.75	254.86	255.11	264.2	0.11	0.36	9.45	9.92	2.030	1.11	3.629	95.262
180	286.1	286.19	286.46	296.07	0.09	0.36	9.97	10.42	2.132	0.86	3.455	95.681
125	243.41	243.58	243.65	258.78	0.17	0.24	15.37	15.78	3.229	1.08	1.521	97.402
90	389.83	390.11	390.38	401.95	0.28	0.55	12.12	12.95	2.650	2.16	4.247	93.591
Pan	394.78	395.78	396.2	407.56	1	1.42	12.78	15.2	3.110	6.58	9.342	84.079
SUM					213.95	158.75	116	**488.7**				

% of diff particles in total	
Coarse [g]	43.77941477
Mid [g]	32.4841416
Fine [g]	23.73644363

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.01	0.00	0.00
	5000	0.08	0.00	0.03
	4000	4.57	0.14	0.11
	2800	33.60	2.82	0.28
	2000	31.83	7.26	0.41
	1400	22.96	25.46	1.66
	1000	5.67	40.44	6.59
	710	0.30	15.59	10.91
	500	0.13	5.83	19.53
	355	0.06	0.62	9.02
	250	0.05	0.23	8.15
	180	0.04	0.23	8.59
	125	0.08	0.15	13.25
	90	0.13	0.35	10.45
Pan	0	0.47	0.89	11.02

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
99.99	100.00	100.0
99.91	100.00	100.0
95.34	99.86	99.9
61.74	97.05	99.6
29.91	89.78	99.2
6.95	64.33	97.5
1.28	23.89	90.9
0.98	8.30	80.0
0.85	2.46	60.5
0.79	1.85	51.5
0.74	1.62	43.3
0.70	1.39	34.7
0.62	1.24	21.5
0.49	0.89	11.0
0.02	0.00	0.0

Size	Tromp 1 (%)	Tromp 2 (%)
4500	96.54	98.72
3400	93.75	99.58
2400	85	99.40
1700	53.71	97.89
1200	14.45	90.90
855	1.68	66.73
605	0.84	29.61
427.5	1.12	9.59
302.5	1.11	4.74
215	0.86	4.32
152.5	1.07	2.60
107.5	2.16	6.41

Figure A.2: PSD data table of cement sample for speed 12m/s

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.47	559.49	559.49	559.5	0.02	0.02	0.03	0.07	0.014	28.57	28.57	42.86
5000	576.67	576.82	576.7	576.71	0.15	0.03	0.04	0.22	0.045	68.18	13.64	18.18
4000	549.36	557.82	549.88	549.36	8.46	0.52	0	8.98	1.822	94.21	5.79	0.00
2800	552.6	626.02	559.6	552.76	73.42	7	0.16	80.58	16.345	91.11	8.69	0.20
2000	565.78	648.9	584.82	566.23	83.12	19.04	0.45	102.61	20.813	81.01	18.56	0.44
1400	386.98	432.49	427.21	388.65	45.51	40.23	1.67	87.41	17.730	52.06	46.02	1.91
1000	362.92	370.93	405.45	367.09	8.01	42.53	4.17	54.71	11.097	14.64	77.74	7.62
Pan	344.98	352.23	385.05	445.32	7.25	40.07	100.34					
710	501.74	502.8	525.3	510.56	1.06	23.56	8.82	33.44	6.783	3.17	70.45	26.38
500	493.39	494.12	504.68	513.47	0.73	11.29	20.08	32.1	6.511	2.27	35.17	62.55
355	463.63	464.13	465.03	474.26	0.5	1.4	10.63	12.53	2.542	3.99	11.17	84.84
250	254.67	255.01	255.06	264.33	0.34	0.39	9.66	10.39	2.108	3.27	3.75	92.97
180	286.61	287.1	286.94	297.64	0.49	0.33	11.03	11.85	2.404	4.14	2.78	93.08
125	237.71	238.6	243.42	258.89	0.89	5.71	21.18	27.78	5.635	3.20	20.55	76.24
90	389.83	390.78	390.4	401.26	0.95	0.57	11.43	12.95	2.627	7.34	4.40	88.26
Pan	394.7	397.11	396.87	407.5	2.41	2.17	12.8	17.38	3.525	13.87	12.49	73.65
SUM					226.06	154.79	112.15	**493**				

% of diff particles in total	
Coarse [g]	45.85
Mid [g]	31.40
Fine [g]	22.75

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.009	0.01	0.03
	5000	0.066	0.02	0.04
	4000	3.742	0.34	0.00
	2800	32.478	4.52	0.14
	2000	36.769	12.30	0.40
	1400	20.132	25.99	1.49
	1000	3.543	27.48	3.72
	710	0.469	15.22	7.86
	500	0.323	7.29	17.90
	355	0.221	0.90	9.48
	250	0.150	0.25	8.61
	180	0.217	0.21	9.84
	125	0.394	3.69	18.89
	90	0.420	0.37	10.19
Pan	0	1.066	1.40	11.41

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
99.99	99.99	100.0
99.92	99.97	99.9
96.18	99.63	99.9
63.70	95.11	99.8
26.94	82.81	99.4
6.80	56.82	97.9
3.26	29.34	94.2
2.79	14.12	86.3
2.47	6.83	68.4
2.25	5.92	58.9
2.10	5.67	50.3
1.88	5.46	40.5
1.49	1.77	21.6
1.07	1.40	11.4
0.00	0.00	0.0

Size	Tromp 1 (%)	Tromp 2 (%)
4500	94.21	100.00
3400	91.11	99.80
2400	81.01	99.56
1700	52.06	98.09
1200	14.64	92.38
855	3.17	73.62
605	2.27	37.45
427.5	3.99	15.16
302.5	3.27	7.03
215	4.14	6.92
152.5	3.2	23.76
107.5	7.34	11.74

Figure A.3: PSD data table of cement sample for speed 14m/s

Appendix B

PSD Data Table of Steel Sample Case 1

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	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.49	559.51	559.5	559.51	0.02	0.01	0.02	0.05	0.010	40.00	20.00	40.00
5000	576.7	576.71	576.71	576.71	0.01	0.01	0.01	0.03	0.006	33.33	33.33	33.33
4000	549.37	553.92	549.38	549.38	4.55	0.01	0.01	4.57	0.949	99.56	0.22	0.22
2800	552.63	582.83	554.07	552.76	30.2	1.44	0.13	31.77	6.595	95.06	4.53	0.41
2000	565.75	604.12	569	565.85	38.37	3.25	0.1	41.72	8.661	91.97	7.79	0.24
1400	387.04	453	393.59	387.27	65.96	6.55	0.23	72.74	15.100	90.68	9.00	0.32
1000	362.96	438.54	382.61	363.7	75.58	19.65	0.74	95.97	19.923	78.75	20.48	0.77
Pan	394.73	421.52	495.64	503	26.79	100.91	108.27					
710	501.82	518.3	517.34	503.35	16.48	15.52	1.53	33.53	6.961	49.15	46.29	4.56
500	493.34	500.45	535.43	499.35	7.11	42.09	6.01	55.21	11.461	12.88	76.24	10.89
355	463.69	464.25	484.6	473.82	0.56	20.91	10.13	31.6	6.560	1.77	66.17	32.06
250	254.98	255.33	269.32	282.92	0.35	14.34	27.94	42.63	8.850	0.82	33.64	65.54
180	287.6	287.87	289.88	301.71	0.27	2.28	14.11	16.66	3.459	1.62	13.69	84.69
125	243.25	243.68	244.62	261.11	0.43	1.37	17.86	19.66	4.081	2.19	6.97	90.84
90	389.81	390.23	390.8	403.03	0.42	0.99	13.22	14.63	3.037	2.87	6.77	90.36
Pan	344.98	346.02	347.27	362.59	1.04	2.29	17.61	20.94	4.347	4.97	10.936	84.10
SUM					241.35	130.71	109.65	**481.71**				

		% of total mass			Cumulative %		
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.008	0.008	0.018	99.99	99.99	99.98
	5000	0.004	0.008	0.009	99.99	99.98	99.97
	4000	1.885	0.008	0.009	98.10	99.98	99.96
	2800	12.513	1.102	0.119	85.59	98.88	99.84
	2000	15.898	2.486	0.091	69.69	96.39	99.75
	1400	27.330	5.011	0.210	42.36	91.38	99.54
	1000	31.316	15.033	0.675	11.05	76.34	98.87
	710	6.828	11.874	1.395	4.22	64.47	97.47
	500	2.946	32.201	5.481	1.27	32.27	91.99
	355	0.232	15.997	9.238	1.04	16.27	82.75
	250	0.145	10.971	25.481	0.89	5.30	57.27
	180	0.112	1.744	12.868	0.78	3.56	44.40
	125	0.178	1.048	16.288	0.60	2.51	28.12
	90	0.174	0.757	12.057	0.43	1.75	16.06
Pan	0	0.431	1.752	16.060	0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500	99.56	99.781
3400	95.06	99.591
2400	89.82	99.760
1700	90.68	99.684
1200	78.75	99.229
855	49.15	95.437
605	12.88	89.114
427.5	1.77	67.943
302.5	0.82	34.459
215	1.62	15.306
152.5	2.19	9.156
107.5	2.87	9.638

Figure B.1: PSD data table of steel sample for speed 8m/s

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.5	559.5	559.5	559.5	0	0	0	0	0.000	N/A	N/A	N/A
5000	576.7	576.7	576.7	576.7	0	0	0	0	0.000	N/A	N/A	N/A
4000	549.38	552.72	549.38	549.38	3.34	0	0	3.34	0.710	100.00	0.00	0.00
2800	552.62	580.6	554.75	552.75	27.98	2.13	0.13	30.24	6.424	92.53	7.04	0.43
2000	565.78	601.58	570.29	565.84	35.8	4.51	0.06	40.37	8.576	88.68	11.17	0.15
1400	387.06	436.92	408.11	387.51	49.86	21.05	0.45	71.36	15.159	69.87	29.50	0.63
1000	362.95	396.89	420.27	366.7	33.94	57.32	3.75	95.01	20.183	35.72	60.33	3.95
Pan	394.73	402.5	463.07	550.04	7.77	68.34	155.31					
710	501.78	504.78	527.61	507.16	3	25.83	5.38	34.21	7.267	8.77	75.50	15.73
500	493.31	493.83	520.32	518.34	0.52	27.01	25.03	52.56	11.165	0.99	51.39	47.62
355	463.59	463.87	470.59	487.48	0.28	7	23.89	31.17	6.621	0.90	22.46	76.64
250	255.03	255.44	257.82	295.2	0.41	2.79	40.17	43.37	9.213	0.95	6.43	92.62
180	286.91	287.2	287.69	302.92	0.29	0.78	16.01	17.08	3.628	1.70	4.57	93.74
125	243.25	243.88	244.19	260.31	0.63	0.94	17.06	18.63	3.958	3.38	5.05	91.57
90	389.83	390.68	390.96	401.59	0.85	1.13	11.76	13.74	2.919	6.19	8.22	85.59
Pan	345	346.8	347.44	360.43	1.8	2.44	15.43	19.67	4.178	9.15	12.405	78.44
SUM					158.7	152.93	159.12	**470.75**				

% of diff particles in total	
Coarse [g]	33.712
Mid [g]	32.486
Fine [g]	33.801

		% of total mass			Cumulative %		
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000	100.00	100.00	100.00
	5000	0.000	0.000	0.000	100.00	100.00	100.00
	4000	2.105	0.000	0.000	97.90	100.00	100.00
	2800	17.631	1.393	0.082	80.26	98.61	99.92
	2000	22.558	2.949	0.038	57.71	95.66	99.88
	1400	31.418	13.764	0.283	26.29	81.89	99.60
	1000	21.386	37.481	2.357	4.90	44.41	97.24
	710	1.890	16.890	3.381	3.01	27.52	93.86
	500	0.328	17.662	15.730	2.68	9.86	78.13
	355	0.176	4.577	15.014	2.51	5.28	63.12
	250	0.258	1.824	25.245	2.25	3.46	37.87
	180	0.183	0.510	10.062	2.07	2.95	27.81
	125	0.397	0.615	10.721	1.67	2.33	17.09
	90	0.536	0.739	7.391	1.13	1.60	9.70
Pan	0	1.134	1.596	9.697	0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500	100	100.000
3400	92.53	99.570
2400	88.68	99.851
1700	69.87	99.369
1200	35.72	96.053
855	8.77	84.274
605	0.99	52.378
427.5	0.9	23.356
302.5	0.95	7.378
215	1.7	6.265
152.5	3.38	8.427
107.5	6.19	14.410

Figure B.2: PSD data table of steel sample for speed 12m/s

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.5	559.5	559.5	559.5	0	0	0	0	0.000	N/A	N/A	N/A
5000	576.71	576.71	576.71	576.71	0	0	0	0	0.000	N/A	N/A	N/A
4000	549.38	554.1	549.5	549.38	4.72	0.12	0	4.84	1.049	97.52	2.48	0.00
2800	552.65	576.54	556.68	552.74	23.89	4.03	0.09	28.01	6.068	85.29	14.39	0.32
2000	565.76	600.61	579.72	566.24	34.85	13.96	0.48	49.29	10.678	70.70	28.32	0.97
1400	387.04	419.17	432.73	389.95	32.13	45.69	2.91	80.73	17.490	39.80	56.60	3.60
1000	362.94	372.95	421.51	374.21	10.01	58.57	11.27	79.85	17.299	12.54	73.35	14.11
Pan	345	352.29	388.8	512.69	7.29	43.8	167.69					
710	501.81	502.65	521.43	513.4	0.84	19.62	11.59	32.05	6.943	2.62	61.22	36.16
500	493.31	494.03	507.14	528.48	0.72	13.83	35.17	49.72	10.771	1.45	27.82	70.74
355	463.63	464.2	466.58	494.55	0.57	2.95	30.92	34.44	7.461	1.66	8.57	89.78
250	254.82	255.55	256.22	292.41	0.73	1.4	37.59	39.72	8.605	1.84	3.52	94.64
180	286.78	287.36	287.45	301.98	0.58	0.67	15.2	16.45	3.564	3.53	4.07	92.40
125	243.24	244.19	244.15	259.21	0.95	0.91	15.97	17.83	3.863	5.33	5.10	89.57
90	389.8	390.86	390.9	399.6	1.06	1.1	9.8	11.96	2.591	8.86	9.20	81.94
Pan	394.72	396.62	397.84	406.4	1.9	3.12	11.68	16.7	3.618	11.38	18.683	69.94
SUM					112.95	165.97	182.67	**461.59**				

% of diff particles in total	
Coarse [g]	24.470
Mid [g]	35.956
Fine [g]	39.574

		% of total mass			Cumulative %		
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000	100.00	100.00	100.00
	5000	0.000	0.000	0.000	100.00	100.00	100.00
	4000	4.179	0.072	0.000	95.82	99.93	100.00
	2800	21.151	2.428	0.049	74.67	97.50	99.95
	2000	30.854	8.411	0.263	43.82	89.09	99.69
	1400	28.446	27.529	1.593	15.37	61.56	98.09
	1000	8.862	35.290	6.170	6.51	26.27	91.93
	710	0.744	11.821	6.345	5.76	14.45	85.58
	500	0.637	8.333	19.253	5.13	6.12	66.33
	355	0.505	1.777	16.927	4.62	4.34	49.40
	250	0.646	0.844	20.578	3.98	3.49	28.82
	180	0.514	0.404	8.321	3.46	3.09	20.50
	125	0.841	0.548	8.743	2.62	2.54	11.76
	90	0.938	0.663	5.365	1.68	1.88	6.39
Pan	0	1.682	1.880	6.394	0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500	97.52	100.000
3400	85.29	99.679
2400	70.7	99.026
1700	39.8	96.395
1200	12.54	85.886
855	2.62	63.838
605	1.45	29.264
427.5	1.66	10.221
302.5	1.84	5.363
215	3.53	7.599
152.5	5.33	10.432
107.5	8.86	18.060

Figure B.3: PSD data table of steel sample for speed 14m/s

Appendix C

PSD Data Table of Cement Sample Case 2

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.51	559.52	559.53	559.52	0.01	0.02	0.01	0.04	0.008	25.00	50.00	25.00
5000	576.64	576.67	576.66	576.66	0.03	0.02	0.02	0.07	0.014	42.86	28.57	28.57
4000	549.28	549.34	549.33	549.34	0.06	0.05	0.06	0.17	0.034	35.29	29.41	35.29
2800	552.57	567.06	553.2	552.61	14.49	0.63	0.04	15.16	3.053	95.58	4.16	0.26
2000	333.18	524.17	339.26	333.27	190.99	6.08	0.09	197.16	39.700	96.87	3.08	0.05
1400	561	729.96	568.89	561.07	168.96	7.89	0.07	176.92	35.624	95.50	4.46	0.04
1000	362.88	448.81	375.59	363.12	85.93	12.71	0.24	98.88	19.910	86.90	12.85	0.24
Pan	344.96	349.78	347.28	345.84	4.82	2.32	0.88					
710	501.9	503.87	503.35	502	1.97	1.45	0.1	3.52	0.709	55.97	41.19	2.84
500	265.95	266.17	266.3	266	0.22	0.35	0.05	0.62	0.125	35.48	56.45	8.06
355	262.37	262.58	262.65	262.47	0.21	0.28	0.1	0.59	0.119	35.59	47.46	16.95
250	254.73	254.89	254.83	254.92	0.16	0.1	0.19	0.45	0.091	35.56	22.22	42.22
180	401.26	401.43	401.3	401.43	0.17	0.04	0.17	0.38	0.077	44.74	10.53	44.74
125	242.95	243.2	242.97	243.15	0.25	0.02	0.2	0.47	0.095	53.19	4.26	42.55
90	389.77	390.1	389.8	389.87	0.33	0.03	0.1	0.46	0.093	71.74	6.52	21.74
Pan	357.4	358.99	357.5	357.45	1.59	0.1	0.05	1.74	0.350	91.38	5.747	2.87
SUM					465.37	29.77	1.49	**496.63**				

% of diff particles in total	
Coarse [g]	93.706
Mid [g]	5.994
Fine [g]	0.300

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.002	0.067	0.671
	5000	0.006	0.067	1.342
	4000	0.013	0.168	4.027
	2800	3.114	2.116	2.685
	2000	41.040	20.423	6.040
	1400	36.307	26.503	4.698
	1000	18.465	42.694	16.107
	710	0.423	4.871	6.711
	500	0.047	1.176	3.356
	355	0.045	0.941	6.711
	250	0.034	0.336	12.752
	180	0.037	0.134	11.409
	125	0.054	0.067	13.423
	90	0.071	0.101	6.711
Pan	0	0.342	0.336	3.356

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
100.00	99.93	99.33
99.99	99.87	97.99
99.98	99.70	93.96
96.86	97.58	91.28
55.82	77.16	85.23
19.52	50.66	80.54
1.05	7.96	64.43
0.63	3.09	57.72
0.58	1.91	54.36
0.54	0.97	47.65
0.50	0.64	34.90
0.47	0.50	23.49
0.41	0.44	10.07
0.34	0.34	3.36
0.00	0.00	0.00

Size	Tromp 1 (%	Tromp 2 (%)
3400	95.58	99.736
2400	96.87	99.954
1700	95.5	99.960
1200	86.9	99.757
855	55.97	97.159
605		
427.5		
302.5		
215		
152.5		

Figure C.1: PSD data table of cement sample 1-3mm for speed 8m/s

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.51	559.54	559.54	559.52	0.03	0.03	0.01	0.07	0.014	42.86	42.86	14.29
5000	576.64	576.64	576.7	576.69	0	0.06	0.05	0.11	0.022	0.00	54.55	45.45
4000	549.28	549.34	549.34	549.33	0.06	0.06	0.05	0.17	0.034	35.29	35.29	29.41
2800	552.57	564.58	553.1	552.6	12.01	0.53	0.03	12.57	2.534	95.54	4.22	0.24
2000	333.18	487.08	342.56	333.39	153.9	9.38	0.21	163.49	32.956	94.13	5.74	0.13
1400	561	706.86	591.84	561.96	145.86	30.84	0.96	177.66	35.812	82.10	17.36	0.54
1000	362.88	422.06	425.66	365.85	59.18	62.78	2.97	124.93	25.183	47.37	50.25	2.38
Pan	344.96	348.65	354.47	349	3.69	9.51	4.04					
710	501.9	502.96	507.25	502.75	1.06	5.35	0.85	7.26	1.463	14.60	73.69	11.71
500	265.95	266.35	268.65	267.21	0.4	2.7	1.26	4.36	0.879	9.17	61.93	28.90
355	262.37	262.66	263.19	263.58	0.29	0.82	1.21	2.32	0.468	12.50	35.34	52.16
250	254.73	254.83	254.79	254.9	0.1	0.06	0.17	0.33	0.067	30.30	18.18	51.52
180	401.26	401.37	401.33	401.41	0.11	0.07	0.15	0.33	0.067	33.33	21.21	45.45
125	242.95	243.12	243.02	243.08	0.17	0.07	0.13	0.37	0.075	45.95	18.92	35.14
90	389.77	389.95	389.84	389.85	0.18	0.07	0.08	0.33	0.067	54.55	21.21	24.24
Pan	357.4	358.73	357.76	357.5	1.33	0.36	0.1	1.79	0.361	74.30	20.112	5.59
SUM					374.68	113.18	8.23	**496.09**				

% of diff particles in total	
Coarse [g]	75.527
Mid [g]	22.814
Fine [g]	1.659

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.008	0.027	0.122
	5000	0.000	0.053	0.608
	4000	0.016	0.053	0.608
	2800	3.205	0.468	0.365
	2000	41.075	8.288	2.552
	1400	38.929	27.249	11.665
	1000	15.795	55.469	36.087
	710	0.283	4.727	10.328
	500	0.107	2.386	15.310
	355	0.077	0.725	14.702
	250	0.027	0.053	2.066
	180	0.029	0.062	1.823
	125	0.045	0.062	1.580
	90	0.048	0.062	0.972
Pan	0	0.355	0.318	1.215

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
99.99	99.97	99.88
99.99	99.92	99.27
99.98	99.87	98.66
96.77	99.40	98.30
55.70	91.11	95.75
16.77	63.86	84.08
0.97	8.39	48.00
0.69	3.67	37.67
0.58	1.28	22.36
0.50	0.56	7.65
0.48	0.50	5.59
0.45	0.44	3.77
0.40	0.38	2.19
0.35	0.32	1.22
0.00	0.00	0.00

Size	Tromp 1 (%	Tromp 2 (%)
3400	95.54	99.761
2400	94.13	99.872
1700	82.1	99.460
1200	47.37	97.623
855	14.6	88.292
605	9.17	71.101
427.5	12.5	47.845

Figure C.2: PSD data table of cement sample 1-3mm for speed 12m/s

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.51	559.58	559.54	559.52	0.07	0.03	0.01	0.11	0.022	63.64	27.27	9.09
5000	576.64	576.75	576.7	576.66	0.11	0.06	0.02	0.19	0.038	57.89	31.58	10.53
4000	549.28	549.41	549.37	549.31	0.13	0.09	0.03	0.25	0.050	52.00	36.00	12.00
2800	552.57	565.36	553.51	552.61	12.79	0.94	0.04	13.77	2.750	92.88	6.83	0.29
2000	333.18	481.34	360	334.06	148.16	26.82	0.88	175.86	35.121	84.25	15.25	0.50
1400	561	653.32	642.36	564.47	92.32	81.36	3.47	177.15	35.379	52.11	45.93	1.96
1000	362.88	384.9	452.25	372.81	22.02	89.37	9.93	121.32	24.229	18.15	73.66	8.18
Pan	344.96	347.64	349.66	349.06	2.68	4.7	4.1					
710	501.9	502.5	504.83	503.75	0.6	2.93	1.85	5.38	1.074	11.15	54.46	34.39
500	265.95	266.32	266.57	267.14	0.37	0.62	1.19	2.18	0.435	16.97	28.44	54.59
355	262.37	262.63	262.54	263.12	0.26	0.17	0.75	1.18	0.236	22.03	14.41	63.56
250	254.73	254.81	254.78	254.83	0.08	0.05	0.1	0.23	0.046	34.78	21.74	43.48
180	401.26	401.37	401.35	401.32	0.11	0.09	0.06	0.26	0.052	42.31	34.62	23.08
125	242.95	243.07	243.04	242.98	0.12	0.09	0.03	0.24	0.048	50.00	37.50	12.50
90	389.77	389.91	389.87	389.81	0.14	0.1	0.04	0.28	0.056	50.00	35.71	14.29
Pan	357.4	358.99	358.08	357.45	1.59	0.68	0.05	2.32	0.463	68.53	29.310	2.16
SUM					278.87	203.4	18.45	**500.72**				

% of diff particles in total	
Coarse [g]	55.694
Mid [g]	40.622
Fine [g]	3.685

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.025	0.015	0.054
	5000	0.039	0.029	0.108
	4000	0.047	0.044	0.163
	2800	4.586	0.462	0.217
	2000	53.129	13.186	4.770
	1400	33.105	40.000	18.808
	1000	7.896	43.938	53.821
	710	0.215	1.441	10.027
	500	0.133	0.305	6.450
	355	0.093	0.084	4.065
	250	0.029	0.025	0.542
	180	0.039	0.044	0.325
	125	0.043	0.044	0.163
	90	0.050	0.049	0.217
Pan	0	0.570	0.334	0.271

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
99.97	99.99	99.95
99.94	99.96	99.84
99.89	99.91	99.67
95.30	99.45	99.46
42.17	86.26	94.69
9.07	46.26	75.88
1.17	2.33	22.06
0.96	0.88	12.03
0.82	0.58	5.58
0.73	0.50	1.52
0.70	0.47	0.98
0.66	0.43	0.65
0.62	0.38	0.49
0.57	0.33	0.27
0.00	0.00	0.00

Size	Tromp 1 (%	Tromp 2 (%)
3400	92.88	99.710
2400	84.25	99.500
1700	52.11	98.041
1200	18.15	91.815
855	11.15	65.613
605		
427.5		
302.5		
215		
152.5		

Figure C.3: PSD data table of cement sample 1-3mm for speed 14m/s

	Weight sample with sieve/pan				Weight sample							
Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.51	559.51	559.51	559.51	0	0	0	0	0.000	0.00	0.00	0.00
5000	576.64	576.66	576.66	576.66	0.02	0.02	0.02	0.06	0.012	33.33	33.33	33.33
4000	549.28	549.31	549.31	549.3	0.03	0.03	0.02	0.08	0.016	37.50	37.50	25.00
2800	552.57	552.61	552.61	552.59	0.04	0.04	0.02	0.1	0.020	40.00	40.00	20.00
2000	333.18	333.45	333.27	333.27	0.27	0.09	0.09	0.45	0.091	60.00	20.00	20.00
1400	561	561.62	561.05	561	0.62	0.05	0	0.67	0.136	92.54	7.46	0.00
1000	362.88	395.99	370.9	363	33.11	8.02	0.12	41.25	8.346	80.27	19.44	0.29
Pan	344.96	461.8	658.13	367.25	116.84	313.17	22.29					
710	501.9	603.19	624.41	504.57	101.29	122.51	2.67	226.47	45.819	44.73	54.10	1.18
500	265.95	280.49	418.35	275.5	14.54	152.4	9.55	176.49	35.707	8.24	86.35	5.41
355	262.37	262.63	299.6	271.8	0.26	37.23	9.43	46.92	9.493	0.55	79.35	20.10
250	254.73	254.74	254.88	254.92	0.01	0.15	0.19	0.35	0.071	2.86	42.86	54.29
180	401.26	401.3	401.38	401.41	0.04	0.12	0.15	0.31	0.063	12.90	38.71	48.39
125	242.95	242.96	243.03	243.08	0.01	0.08	0.13	0.22	0.045	4.55	36.36	59.09
90	389.77	389.81	389.86	389.84	0.04	0.09	0.07	0.2	0.040	20.00	45.00	35.00
Pan	357.4	357.59	357.83	357.48	0.19	0.43	0.08	0.7	0.142	27.14	61.429	11.43
SUM					150.47	321.26	22.54	**494.27**				

% of diff particles in total	
Coarse [g]	30.443
Mid [g]	64.997
Fine [g]	4.560

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000
	5000	0.013	0.006	0.089
	4000	0.020	0.009	0.089
	2800	0.027	0.012	0.089
	2000	0.179	0.028	0.399
	1400	0.412	0.016	0.000
	1000	22.004	2.496	0.532
	710	67.316	38.134	11.846
	500	9.663	47.438	42.369
	355	0.173	11.589	41.837
	250	0.007	0.047	0.843
	180	0.027	0.037	0.665
	125	0.007	0.025	0.577
	90	0.027	0.028	0.311
Pan	0	0.126	0.134	0.355

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
100.00	100.00	100.00
99.99	99.99	99.91
99.97	99.98	99.82
99.94	99.97	99.73
99.76	99.94	99.33
99.35	99.93	99.33
77.34	97.43	98.80
10.03	59.30	86.96
0.37	11.86	44.59
0.19	0.27	2.75
0.19	0.22	1.91
0.16	0.19	1.24
0.15	0.16	0.67
0.13	0.13	0.35
0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400		
2400		
1700		
1200	80.27	99.71
855	44.73	98.82
605	8.24	94.59
427.5	0.55	79.90
302.5		
215		
152.5		
107.5		

Figure C.4: PSD data table of cement sample 0.5-1mm for speed 8m/s

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed	of total fe	% of Coars	% of Mid	% of Fine
5600	559.51	559.51	559.51	559.51	0	0	0	0	0.000	0.00	0.00	0.00
5000	576.64	576.65	576.64	576.64	0.01	0	0	0.01	0.002	100.00	0.00	0.00
4000	549.28	549.29	549.28	549.28	0.01	0	0	0.01	0.002	100.00	0.00	0.00
2800	552.57	552.69	552.6	552.57	0.12	0.03	0	0.15	0.030	80.00	20.00	0.00
2000	333.18	333.28	333.26	333.25	0.1	0.08	0.07	0.25	0.051	40.00	32.00	28.00
1400	561	561.07	561.11	561.02	0.07	0.11	0.02	0.2	0.040	35.00	55.00	10.00
1000	362.88	370.68	398.01	363.95	7.8	35.13	1.07	44	8.893	17.73	79.84	2.43
Pan	344.96	356.61	654.17	474.43	11.65	309.21	129.47					
710	501.9	513.17	691.98	531.28	11.27	190.08	29.38	230.73	46.634	4.88	82.38	12.73
500	265.95	266.19	367.57	336.16	0.24	101.62	70.21	172.07	34.778	0.14	59.06	40.80
355	262.37	262.37	278.94	291.11	0	16.57	28.74	45.31	9.158	0.00	36.57	63.43
250	254.73	254.73	254.84	254.96	0	0.11	0.23	0.34	0.069	0.00	32.35	67.65
180	401.26	401.26	401.4	401.45	0	0.14	0.19	0.33	0.067	0.00	42.42	57.58
125	242.95	242.95	243.07	243.12	0	0.12	0.17	0.29	0.059	0.00	41.38	58.62
90	389.77	389.77	389.88	389.87	0	0.11	0.1	0.21	0.042	0.00	52.38	47.62
Pan	357.4	357.43	357.91	357.73	0.03	0.51	0.33	0.87	0.176	3.45	58.621	37.93
SUM					19.65	344.61	130.51	**494.77**				

% of diff particles in total	
Coarse [g]	3.972
Mid [g]	69.651
Fine [g]	26.378

	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000
	5000	0.051	0.000	0.000
	4000	0.051	0.000	0.000
	2800	0.611	0.009	0.000
	2000	0.509	0.023	0.054
	1400	0.356	0.032	0.015
	1000	39.695	10.194	0.820
	710	57.354	55.158	22.512
	500	1.221	29.488	53.797
	355	0.000	4.808	22.021
	250	0.000	0.032	0.176
	180	0.000	0.041	0.146
	125	0.000	0.035	0.130
	90	0.000	0.032	0.077
Pan	0	0.153	0.148	0.253

Coarse[g]	Mid [g]	Fine[g]
100.00	100.00	100.00
99.95	100.00	100.00
99.90	100.00	100.00
99.29	99.99	100.00
98.78	99.97	99.95
98.42	99.94	99.93
58.73	89.74	99.11
1.37	34.58	76.60
0.15	5.10	22.80
0.15	0.29	0.78
0.15	0.26	0.61
0.15	0.21	0.46
0.15	0.18	0.33
0.15	0.15	0.25
0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400		
2400		
1700		
1200	17.73	97.568
855	4.88	87.267
605	0.14	59.197
427.5	0	36.570
302.5		
215		
152.5		
107.5		

Figure C.5: PSD data table of cement sample 0.5-1mm for speed 12m/s

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed	of total fe	% of Coarse	% of Mid	% of Fine
5600	559.51	559.51	559.51	559.51	0	0	0	0	0.000	0.00	0.00	0.00
5000	576.64	576.64	576.64	576.64	0	0	0	0	0.000	0.00	0.00	0.00
4000	549.28	549.28	549.28	549.28	0	0	0	0	0.000	0.00	0.00	0.00
2800	552.57	552.57	552.57	552.57	0	0	0	0	0.000	0.00	0.00	0.00
2000	333.18	333.26	333.26	333.18	0.08	0.08	0	0.16	0.032	50.00	50.00	0.00
1400	561	561.03	561.07	561.03	0.03	0.07	0.03	0.13	0.026	23.08	53.85	23.08
1000	362.88	364.91	406.68	366.06	2.03	43.8	3.18	49.01	9.908	4.14	89.37	6.49
Pan	344.96	347.09	580.9	552.06	2.13	235.94	207.1					
710	501.9	503.88	673.22	569.44	1.98	171.32	67.54	240.84	48.690	0.82	71.13	28.04
500	265.95	266.05	322.6	373.2	0.1	56.65	107.25	164	33.155	0.06	34.54	65.40
355	262.37	262.37	269.55	293.5	0	7.18	31.13	38.31	7.745	0.00	18.74	81.26
250	254.73	254.73	254.78	255.01	0	0.05	0.28	0.33	0.067	0.00	15.15	84.85
180	401.26	401.26	401.35	401.49	0	0.09	0.23	0.32	0.065	0.00	28.13	71.87
125	242.95	242.95	243.06	243.15	0	0.11	0.2	0.31	0.063	0.00	35.48	64.52
90	389.77	389.78	389.87	389.9	0.01	0.1	0.13	0.24	0.049	4.17	41.67	54.17
Pan	357.4	357.44	357.91	357.84	0.04	0.51	0.44	0.99	0.200	4.04	51.515	44.44
SUM					4.27	279.96	210.41	**494.64**				

% of diff particles in total	
Coarse [g]	0.863
Mid [g]	56.599
Fine [g]	42.538

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000
	5000	0.000	0.000	0.000
	4000	0.000	0.000	0.000
	2800	0.000	0.000	0.000
	2000	1.874	0.029	0.000
	1400	0.703	0.025	0.014
	1000	47.541	15.645	1.511
	710	46.370	61.194	32.099
	500	2.342	20.235	50.972
	355	0.000	2.565	14.795
	250	0.000	0.018	0.133
	180	0.000	0.032	0.109
	125	0.000	0.039	0.095
	90	0.234	0.036	0.062
Pan	0	0.937	0.182	0.209

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
100.00	100.00	100.00
100.00	100.00	100.00
100.00	100.00	100.00
100.00	100.00	100.00
98.13	99.97	100.00
97.42	99.95	99.99
49.88	84.30	98.47
3.51	23.11	66.38
1.17	2.87	15.40
1.17	0.31	0.61
1.17	0.29	0.48
1.17	0.26	0.37
1.17	0.22	0.27
0.94	0.18	0.21
0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400		
2400		
1700		
1200	4.14	93.512
855	0.82	71.956
605	0.06	34.604
427.5	0	18.742
302.5		
215		
152.5		
107.5		

Figure C.6: PSD data table of cement sample 0.5-1mm for speed 14m/s

Appendix D

PSD Data Table of Steel Sample Case 2

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.47	559.51	559.5	559.52	0.04	0.03	0.05	0.12	0.024	0.00	0.00	0.00
5000	576.64	576.66	576.65	576.69	0.02	0.01	0.05	0.08	0.016	25.00	12.50	62.50
4000	549.29	549.32	549.3	549.33	0.03	0.01	0.04	0.08	0.016	37.50	12.50	50.00
2800	552.6	552.62	552.6	552.64	0.02	0	0.04	0.06	0.012	33.33	0.00	66.67
2000	333.25	333.27	333.26	333.3	0.02	0.01	0.05	0.08	0.016	25.00	12.50	62.50
1400	561	561.05	561.06	561.04	0.05	0.06	0.04	0.15	0.030	33.33	40.00	26.67
1000	362.94	371.56	365.06	363.03	8.62	2.12	0.09	10.83	2.185	79.59	19.58	0.83
Pan	345.02	466.04	669.68	382.31	121.02	324.66	37.29					
710	501.79	585.05	578.62	503.63	83.26	76.83	1.84	161.93	32.677	51.42	47.45	1.14
500	265.96	301.03	460.14	283.41	35.07	194.18	17.45	246.7	49.783	14.22	78.71	7.07
355	463.53	465.93	515.97	481.29	2.4	52.44	17.76	72.6	14.650	3.31	72.23	24.46
250	254.69	254.73	254.88	254.76	0.04	0.19	0.07	0.3	0.061	13.33	63.33	23.33
180	401.23	401.29	401.42	401.28	0.06	0.19	0.05	0.3	0.061	20.00	63.33	16.67
125	242.9	242.95	243.08	243.94	0.05	0.18	1.04	1.27	0.256	3.94	14.17	81.89
90	389.75	389.83	389.91	389.75	0.08	0.16	0	0.24	0.048	33.33	66.67	0.00
Pan	394.74	394.88	395.39	394.76	0.14	0.65	0.02	0.81	0.163	17.28	80.247	2.47
SUM					129.9	327.06	38.59	**495.55**				

% of diff particles in total	
Coarse [g]	26.213
Mid [g]	65.999
Fine [g]	7.787

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.031	0.009	0.130
	5000	0.015	0.003	0.130
	4000	0.023	0.003	0.104
	2800	0.015	0.000	0.104
	2000	0.015	0.003	0.130
	1400	0.038	0.018	0.104
	1000	6.636	0.648	0.233
	710	64.095	23.491	4.768
	500	26.998	59.371	45.219
	355	1.848	16.034	46.022
	250	0.031	0.058	0.181
	180	0.046	0.058	0.130
	125	0.038	0.055	2.695
	90	0.062	0.049	0.000
Pan	0	0.108	0.199	0.052

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
99.97	99.99	99.87
99.95	99.99	99.74
99.93	99.98	99.64
99.92	99.98	99.53
99.90	99.98	99.40
99.86	99.96	99.30
93.23	99.32	99.07
29.13	75.82	94.30
2.13	16.45	49.08
0.28	0.42	3.06
0.25	0.36	2.88
0.21	0.30	2.75
0.17	0.25	0.05
0.11	0.20	0.05
0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400		
2400		
1700		
1200	79.59	99.169
855	51.42	98.864
605	14.22	92.927
427.5	3.31	75.537
302.5		
215		
152.5		
107.5		

Figure D.1: PSD data table of steel sample 0.5-1mm for speed 8m/s

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.47	559.47	559.47	559.47	0	0	0	0	0.000	0.00	0.00	0.00
5000	576.64	576.64	576.64	576.64	0	0	0	0	0.000	0.00	0.00	0.00
4000	549.29	549.29	549.29	549.29	0	0	0	0	0.000	0.00	0.00	0.00
2800	552.6	552.6	552.6	552.6	0	0	0	0	0.000	0.00	0.00	0.00
2000	333.25	333.45	333.53	333.38	0.2	0.28	0.13	0.61	0.124	32.79	45.90	21.31
1400	561	561.1	561.44	561.29	0.1	0.44	0.29	0.83	0.169	12.05	53.01	34.94
1000	362.94	366.01	374.71	364.39	3.07	11.77	1.45	16.29	3.307	18.85	72.25	8.90
Pan	345.02	358.33	602.86	548.35	13.31	257.84	203.33					
710	501.79	511.06	629.57	538.4	9.27	127.78	36.61	173.66	35.259	5.34	73.58	21.08
500	265.96	268.24	370.72	381.52	2.28	104.76	115.56	222.6	45.196	1.02	47.06	51.91
355	463.53	465.11	487.74	513.39	1.58	24.21	49.86	75.65	15.360	2.09	32.00	65.91
250	254.69	254.85	255	254.9	0.16	0.31	0.21	0.68	0.138	23.53	45.59	30.88
180	401.23	401.33	401.43	401.37	0.1	0.2	0.14	0.44	0.089	22.73	45.45	31.82
125	242.9	242.96	243.1	243.06	0.06	0.2	0.16	0.42	0.085	14.29	47.62	38.10
90	389.75	389.77	389.92	389.91	0.02	0.17	0.16	0.35	0.071	5.71	48.57	45.71
Pan	394.74	394.77	395.21	395.23	0.03	0.47	0.49	0.99	0.201	3.03	47.475	49.49
SUM					16.87	270.59	205.06	**492.52**				

% of diff particles in total	
Coarse [g]	3.425
Mid [g]	54.940
Fine [g]	41.635

	% of total mass			
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000
	5000	0.000	0.000	0.000
	4000	0.000	0.000	0.000
	2800	0.000	0.000	0.000
	2000	1.186	0.103	0.063
	1400	0.593	0.163	0.141
	1000	18.198	4.350	0.707
	710	54.950	47.223	17.853
	500	13.515	38.715	56.354
	355	9.366	8.947	24.315
	250	0.948	0.115	0.102
	180	0.593	0.074	0.068
	125	0.356	0.074	0.078
	90	0.119	0.063	0.078
Pan	0	0.178	0.174	0.239

Cumulative %		
Coarse[g]	Mid [g]	Fine[g]
100.00	100.00	100.00
100.00	100.00	100.00
100.00	100.00	100.00
100.00	100.00	100.00
98.81	99.90	99.94
98.22	99.73	99.80
80.02	95.38	99.09
25.07	48.16	81.23
11.56	9.45	24.88
2.19	0.50	0.57
1.24	0.38	0.46
0.65	0.31	0.40
0.30	0.24	0.32
0.18	0.17	0.24
0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400		
2400		
1700		
1200	18.85	91.099
855	5.34	78.919
605	1.02	48.086
427.5	2.09	34.091
302.5		
215		
152.5		
107.5		

Figure D.2: PSD data table of steel sample 0.5-1mm for speed 12m/s

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coars	% of Mid	% of Fine
5600	559.47	559.47	559.47	559.47	0	0	0	0	0.000	0.00	0.00	0.00
5000	576.64	576.64	576.64	576.64	0	0	0	0	0.000	0.00	0.00	0.00
4000	549.29	549.29	549.29	549.29	0	0	0	0	0.000	0.00	0.00	0.00
2800	552.6	552.6	552.6	552.6	0	0	0	0	0.000	0.00	0.00	0.00
2000	333.25	334.04	333.29	333.26	0.79	0.04	0.01	0.84	0.169	94.05	4.76	1.19
1400	561	562.63	561.39	561.1	1.63	0.39	0.1	2.12	0.425	76.89	18.40	4.72
1000	363.02	367.12	380.72	365.2	4.1	17.7	2.18	23.98	4.811	17.10	73.81	9.09
Pan	345.08	350.51	577.13	579.08	5.43	232.05	234					
710	501.79	506.21	646.62	567.38	4.42	144.83	65.59	214.84	43.102	2.06	67.41	30.53
500	266.02	266.59	340.45	399.02	0.57	74.43	133	208	41.730	0.27	35.78	63.94
355	463.59	463.93	475.49	497.56	0.34	11.9	33.97	46.21	9.271	0.74	25.75	73.51
250	254.69	254.73	254.79	254.92	0.04	0.1	0.23	0.37	0.074	10.81	27.03	62.16
180	401.3	401.3	401.39	401.47	0	0.09	0.17	0.26	0.052	0.00	34.62	65.38
125	242.9	242.95	243.04	243.09	0.05	0.14	0.19	0.38	0.076	13.16	36.84	50.00
90	389.81	389.82	389.91	389.96	0.01	0.1	0.15	0.26	0.052	3.85	38.46	57.69
Pan	394.78	394.78	395.26	395.48	0	0.48	0.7	1.18	0.237	0.00	40.678	59.32
SUM					11.95	250.2	236.29	**498.44**				

% of diff particles in total	
Coarse [g]	2.397
Mid [g]	50.197
Fine [g]	47.406

	% of total mass				Cumulative %		
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000	100.00	100.00	100.00
	5000	0.000	0.000	0.000	100.00	100.00	100.00
	4000	0.000	0.000	0.000	100.00	100.00	100.00
	2800	0.000	0.000	0.000	100.00	100.00	100.00
	2000	6.611	0.016	0.004	93.39	99.98	100.00
	1400	13.640	0.156	0.042	79.75	99.83	99.95
	1000	34.310	7.074	0.923	45.44	92.75	99.03
	710	36.987	57.886	27.758	8.45	34.87	71.27
	500	4.770	29.748	56.287	3.68	5.12	14.99
	355	2.845	4.756	14.376	0.84	0.36	0.61
	250	0.335	0.040	0.097	0.50	0.32	0.51
	180	0.000	0.036	0.072	0.50	0.29	0.44
	125	0.418	0.056	0.080	0.08	0.23	0.36
	90	0.084	0.040	0.063	0.00	0.19	0.30
Pan	0	0.000	0.192	0.296	0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400		
2400		
1700		
1200	76.89	95.283
855	17.1	90.909
605	2.06	69.470
427.5	0.27	36.058
302.5	0.74	26.488
215		
152.5		
107.5		

t

Category	d_{75}	d_{25}	Sharpness of cut
Tromp 1			
Tromp 2			

14 m/s.. (0.5 -1mm)

Figure D.3: PSD data table of steel sample 0.5-1mm for speed 14m/s

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.47	559.47	559.47	559.47	0	0	0	0	0.000	0.00	0.00	0.00
5000	576.64	576.65	576.64	576.64	0.01	0	0	0.01	0.002	0.00	0.00	0.00
4000	549.31	549.31	549.31	549.31	0	0	0	0	0.000	0.00	0.00	0.00
2800	552.62	554.77	552.62	552.62	2.15	0	0	2.15	0.431	100.00	0.00	0.00
2000	333.25	423.83	334.3	333.26	90.58	1.05	0.01	91.64	18.385	98.84	1.15	0.01
1400	561	731.98	568.25	561.1	170.98	7.25	0.1	178.33	35.776	95.88	4.07	0.06
1000	362.95	524.76	404.44	363.88	161.81	41.49	0.93	204.23	40.972	79.23	20.32	0.46
Pan	345.05	354.79	355.79	346.69	9.74	10.74	1.64					
710	501.76	507.83	508.29	502.19	6.07	6.53	0.43	13.03	2.614	46.58	50.12	3.30
500	266.03	267.18	268.25	266.46	1.15	2.22	0.43	3.8	0.762	30.26	58.42	11.32
355	463.52	464.16	465.05	464.23	0.64	1.53	0.71	2.88	0.578	22.22	53.12	24.65
250	254.68	254.81	254.75	254.73	0.13	0.07	0.05	0.25	0.050	52.00	28.00	20.00
180	401.26	401.38	401.29	401.28	0.12	0.03	0.02	0.17	0.034	70.59	17.65	11.76
125	242.9	243.11	242.97	242.93	0.21	0.07	0.03	0.31	0.062	67.74	22.58	9.68
90	389.76	389.96	389.81	389.77	0.2	0.05	0.01	0.26	0.052	76.92	19.23	3.85
Pan	394.75	395.98	394.92	394.75	1.23	0.17	0	1.4	0.281	87.86	12.143	0.00
SUM					435.28	60.46	2.72	**498.46**				

% of diff particles in total	
Coarse [g]	87.325
Mid [g]	12.129
Fine [g]	0.546

	% of total mass				cumulative %		
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.000	100.00	100.00	100.00
	5000	0.002	0.000	0.000	100.00	100.00	100.00
	4000	0.000	0.000	0.000	100.00	100.00	100.00
	2800	0.494	0.000	0.000	99.50	100.00	100.00
	2000	20.810	1.737	0.368	78.69	98.26	99.63
	1400	39.280	11.991	3.676	39.41	86.27	95.96
	1000	37.174	68.624	34.191	2.24	17.65	61.76
	710	1.395	10.801	15.809	0.85	6.85	45.96
	500	0.264	3.672	15.809	0.58	3.18	30.15
	355	0.147	2.531	26.103	0.43	0.65	4.04
	250	0.030	0.116	1.838	0.40	0.53	2.21
	180	0.028	0.050	0.735	0.38	0.48	1.47
	125	0.048	0.116	1.103	0.33	0.36	0.37
	90	0.046	0.083	0.368	0.28	0.28	0.00
Pan	0	0.283	0.281	0.000	0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400		
2400	98.84	99.989
1700	95.88	99.944
1200	79.23	99.545
855	46.58	96.700
605	30.26	88.684
427.5		
302.5		
215		
152.5		
107.5		

Figure D.4: PSD data table of steel sample 1-3mm for speed 8m/s

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.46	559.46	559.46	559.48	0	0	0.02	0.02	0.004	0.00	0.00	100.00
5000	576.65	576.65	576.67	576.67	0	0.02	0.02	0.04	0.008	0.00	50.00	50.00
4000	549.31	549.42	549.35	549.32	0.11	0.04	0.01	0.16	0.032	68.75	25.00	6.25
2800	552.59	554.68	552.67	552.6	2.09	0.08	0.01	2.18	0.437	95.87	3.67	0.46
2000	333.24	410.7	340.18	333.56	77.46	6.94	0.32	84.72	16.981	91.43	8.19	0.38
1400	561	682.72	611.21	563.24	121.72	50.21	2.24	174.17	34.910	69.89	28.83	1.29
1000	362.96	434.02	498.27	377.33	71.06	135.31	14.37	220.74	44.245	32.19	61.30	6.51
Pan	345.05	357.95	353.76	349.95	12.9	8.71	4.9					
710	501.75	503.42	508.73	505.28	1.67	6.98	3.53	12.18	2.441	13.71	57.31	28.98
500	265.99	266.1	266.43	266.7	0.11	0.44	0.71	1.26	0.253	8.73	34.92	56.35
355	463.52	463.62	463.71	463.98	0.1	0.19	0.46	0.75	0.150	13.33	25.33	61.33
250	254.7	254.77	254.76	254.73	0.07	0.06	0.03	0.16	0.032	43.75	37.50	18.75
180	401.27	401.35	401.36	401.29	0.08	0.09	0.02	0.19	0.038	42.11	47.37	10.53
125	242.93	243.05	243.04	242.93	0.12	0.11	0	0.23	0.046	52.17	47.83	0.00
90	389.78	389.9	389.92	389.78	0.12	0.14	0	0.26	0.052	46.15	53.85	0.00
Pan	394.74	395.935	395.37	394.76	1.195	0.63	0.02	1.845	0.370	64.77	34.146	1.08
SUM					275.905	201.24	21.76	**498.91**				

% of diff particles in total	
Coarse [g]	55.302
Mid [g]	40.336
Fine [g]	4.362

	% of total mass				cumulative %		
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.000	0.092	100.00	100.00	99.91
	5000	0.000	0.010	0.092	100.00	99.99	99.82
	4000	0.040	0.020	0.046	99.96	99.97	99.77
	2800	0.758	0.040	0.046	99.20	99.93	99.72
	2000	28.075	3.449	1.471	71.13	96.48	98.25
	1400	44.117	24.950	10.294	27.01	71.53	87.96
	1000	25.755	67.238	66.039	1.26	4.29	21.92
	710	0.605	3.468	16.222	0.65	0.82	5.70
	500	0.040	0.219	3.263	0.61	0.61	2.44
	355	0.036	0.094	2.114	0.57	0.51	0.32
	250	0.025	0.030	0.138	0.55	0.48	0.18
	180	0.029	0.045	0.092	0.52	0.44	0.09
	125	0.043	0.055	0.000	0.48	0.38	0.09
	90	0.043	0.070	0.000	0.43	0.31	0.09
Pan	0	0.433	0.313	0.092	0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400	95.87	99.541
2400	91.43	99.622
1700	69.89	98.714
1200	32.19	93.490
855	13.71	71.018
605		
427.5		
302.5		
215		
152.5		
107.5		

Figure D.5: PSD data table of steel sample 1-3mm for speed 12m/s

Sieve [µm]	Empty [g]	Coarse [g]	Mid [g]	Fine [g]	Coarse [g]	Mid [g]	Fine [g]	Total Feed [g]	% of total feed	% of Coarse	% of Mid	% of Fine
5600	559.46	559.46	559.47	559.48	0	0.01	0.02	0.03	0.006	0.00	33.33	66.67
5000	576.65	576.67	576.66	576.68	0.02	0.01	0.03	0.06	0.012	33.33	16.67	50.00
4000	549.31	549.33	549.31	549.35	0.02	0	0.04	0.06	0.012	33.33	0.00	66.67
2800	552.59	555.23	553.05	552.62	2.64	0.46	0.03	3.13	0.637	84.35	14.70	0.96
2000	333.24	406.9	350.59	333.88	73.66	17.35	0.64	91.65	18.666	80.37	18.93	0.70
1400	561	645.01	649.44	567.78	84.01	88.44	6.78	179.23	36.503	46.87	49.34	3.78
1000	362.96	391.96	505.18	395.19	29	142.22	32.23	203.45	41.436	14.25	69.90	15.84
Pan	345.05	346.31	351.59	350.68	1.26	6.54	5.63					
710	501.75	502.24	506.59	506.36	0.49	4.84	4.61	9.94	2.024	4.93	48.69	46.38
500	265.99	266.04	266.17	266.39	0.05	0.18	0.4	0.63	0.128	7.94	28.57	63.49
355	463.52	463.58	463.64	463.79	0.06	0.12	0.27	0.45	0.092	13.33	26.67	60.00
250	254.7	254.75	254.82	254.78	0.05	0.12	0.08	0.25	0.051	20.00	48.00	32.00
180	401.27	401.31	401.4	401.34	0.04	0.13	0.07	0.24	0.049	16.67	54.17	29.17
125	242.93	243	243.11	243	0.07	0.18	0.07	0.32	0.065	21.87	56.25	21.87
90	389.78	389.85	389.94	389.82	0.07	0.16	0.04	0.27	0.055	25.93	59.26	14.81
Pan	394.74	395.08	395.57	394.86	0.34	0.83	0.12	1.29	0.263	26.36	64.341	9.30
SUM					190.52	255.05	45.43	**491.00**				

% of diff particles in total	
Coarse [g]	38.802
Mid [g]	51.945
Fine [g]	9.253

	% of total mass				cumulative %		
	Sieve [µm]	Coarse[g]	Mid [g]	Fine[g]	Coarse[g]	Mid [g]	Fine[g]
	5600	0.000	0.004	0.044	100.00	100.00	99.96
	5000	0.010	0.004	0.066	99.99	99.99	99.89
	4000	0.010	0.000	0.088	99.98	99.99	99.80
	2800	1.386	0.180	0.066	98.59	99.81	99.74
	2000	38.663	6.803	1.409	59.93	93.01	98.33
	1400	44.095	34.676	14.924	15.84	58.33	83.40
	1000	15.221	55.762	70.944	0.61	2.57	12.46
	710	0.257	1.898	10.147	0.36	0.67	2.31
	500	0.026	0.071	0.880	0.33	0.60	1.43
	355	0.031	0.047	0.594	0.30	0.56	0.84
	250	0.026	0.047	0.176	0.27	0.51	0.66
	180	0.021	0.051	0.154	0.25	0.46	0.51
	125	0.037	0.071	0.154	0.22	0.39	0.35
	90	0.037	0.063	0.088	0.18	0.33	0.26
Pan	0	0.178	0.325	0.264	0.00	0.00	0.00

Size	Tromp 1 (%)	Tromp 2 (%)
4500		
3400	84.35	99.042
2400	80.37	99.302
1700	46.87	96.217
1200	14.25	84.158
855	4.93	53.622
605		
427.5		
302.5		
215		
152.5		
107.5		

Figure D.6: PSD data table of steel sample 1-3mm for speed 14m/s