Design and Development of Flexible Screen for Processing Industries and its Performance Prediction using Machine Learning Techniques

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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DECLARATION

by the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitiled **"Design and Development of Flexible Screen for Processing Industries and its Performance Prediction using Machine Learning Techniques"** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Mining Engineering** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to certify that the Research Thesis entitled "**Design and Development of Flexible Screen for Processing Industries and its Performance Prediction using Machine Learning Techniques**" submitted by **Mr. Bharath Kumar S** (**Register Number:** 177059MN002) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy.

11/9/2023 11/9/23

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Dedicated to my mother Mrs. Nagarathna S, my father Mr. Shanmugam K G, my wife Mrs. Shobha Rani K, my dear son Srivatsav S B and my family

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ABSTRACT

In the material processing industry, screening is one of the crucial physical separation methods to separate the undersized fine particles from the oversized coarse particles. The availability of low-grade coal and iron ore with high impurities has urged the improvisation of processing equipment such as screening machines with higher efficiency without utilising water. Previous studies showed that wet processing of coal and iron ore was carried out with enormous quantities of water and also required a water treatment circuit in the plant to treat the tailings. Dry processing has significant merits in preventing water consumption, eliminating waste, and tailing water treatment.
The major problems of the existing dry processing linear vibratory screening machine are lower efficiency caused by the screen clogging, high velocity, reduced residence time, and inflexibility in changing the angular position and frequency of the screen. The efficiency of the existing linear vibrating screen available at the JSW (Jindal Steel Works) steel plant, as well as that available in the Department of Mining Engineering, NITK Surathkal (lab scale), was around 65.00%.

So, a new screening machine was designed and developed to overcome all the limitations of the existing linear vibratory screening machine. The new screening machine was developed with a circular mode of vibration for dry screening of moist coal and iron ore of size fraction −4mm + 0 mm. A screen mesh of 2 mm aperture size was used to separate the fine coal and iron ore particles of size fraction −2 mm + 0 mm individually. The new screening machine has the flexibility to vary the operational parameters, such as the angle in an upward sloping direction and the vibration frequency of the screen, and it can work as a feeder.

Experimental investigations were conducted at the JSW R&D laboratory to assess the efficiency of screening coal and iron ore of varying moisture content of 4%, 6%, and 8% in the new screening machine. Before the screening, the angle and frequency were set by adjusting the angle bolts and frequency drive, respectively. During the screening, the samples were fed to the screen at 8.33 kg/min and undersize particles were collected. The collected samples were weighed, and the screening efficiency was calculated for coal and iron ore samples.

The test results showed that the screening machine could provide higher efficiency for screening iron ore than coal material. Further, the screening efficiency of coal and iron ore was predicted using a machine learning (supervised learning) prediction model such as polynomial regression and backpropagation artificial neural network (ANN) models. The results showed that for all experimental conditions, compared to the second-order polynomial regression modelling, the ANN modeling was a better mathematical modeling technique suitable for predicting the screening machine's performance.

Further, the residual analysis of each prediction model was analysed and validated using a normal probability plot and histogram. Additionally, the developed screening machine's operational parameters were optimised using the Taguchi L27 Design of Experiments technique to obtain a high response parameter, i.e., screening efficiency. For the optimisation study, the operational parameters considered were moisture content, angle, and frequency. The Taguchi L27 optimisation results yielded a higher screening efficiency of 84.40% for coal and 94.53% for iron ore. Furthermore, the Pareto chart and normal effect plot were developed using a fractional Design of Experiments (DOE) to evaluate the significant operational parameter for the screening machine. The results of the fractional Design of Experiments on coal and iron ore show the moisture content as the most significant operational parameter, followed by the angle and frequency. Additionally, the feeding performance of coal and iron ore was improved by transforming the screening machine into a feeding machine by replacing the screen mesh with a thin solid plate. The results showed that the developed machine could be utilised as a multifunctional machine for efficient screening with less clogging and also as an efficient feeder.

Key words: Screening machine, Iron ore, Coal, Regression, Artificial neural network (ANN), Taguchi L27, Fractional Design of Experiments

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

1. INTRODUCTION

1.1 General

The screening process is usually carried out to separate two or more materials of different particle size fractions (Anthony et al. 2007). Vibratory screening machines have various applications in the material processing industry to screen minerals, mineral ores, and ore slurries (Nigel et al. 2009). It also has applications in the mining industry, especially the coal mining industry (Johnson et al. 2006). Other screening applications are in the cement, food, and pharmaceutical sectors (Anthony et al. 2007; Wodzinski 2003; Xiao and Tong 2013; Zhanfu et al. 2015; Makinde et al. 2015). Screening is an important physical separation method for separating the undersized fine particles from the oversized coarse particles (Soldinger 1999; Soldinger 2000; Elskamp et al. 2016, 2015; Zhao et al. 2017; Davoodi et al. 2019). In screening, the amount of fine material collected depends on the stratification rate and the flow rate of particles through the screen apertures (Soldinger et al. 1999). Stratification is the passing of fine particles through the gap of coarse particles when the screen is provided with motion (Soldinger et al. 1999). The screening machine utilises a screen to separate particles by providing vibratory, oscillatory, or gyratory motion to the screen (William et al. 1981).

1.2 Limitations of wet processing

Initially, wet processing was utilised to separate materials (Zhovtiuk 2007). Wet beneficiation utilises an enormous quantity of water and requires a water treatment circuit in the plant to treat the tailings. In some areas of India, China, Australia, South Africa, and the United States, material processing was difficult to carry out due to the scarcity of water (Zhao et al. 2011). Hence, it is preferred to develop a highly efficient dry beneficiation technology. Dry processing has numerous merits compared with wet beneficiation (Chalavadi et al. 2016; Çicek 2008). Some of the significant merits are preventing water consumption, eliminating waste, and tailing water treatment. The availability of dry processing techniques for treating fine coal and iron ore is limited (Chalavadi et al. 2016). The total consumption of coal in India was 946.42 million tonnes in 2020, and coal is a prime source of energy for the generation of electricity in the world (Energy Statistics 2021). The reduction in ash content produces high energy-efficient clean coal (Wang et al. 2019). Similarly, Iron ore beneficiation of size less than 2 mm is carried out to reduce gangue material and produce high-grade material (Gülcan and Gülsoy 2017). The requirement for a highly efficient vibrating screen has increased with the requirement for clean coal and iron ore. So, the development of suitable dry processing technology will be most beneficial for material separation.

Several attempts were made to study the dry screening performance of the existing linear vibratory screening machine (Kumar et al. 2018). In an existing linear vibratory screening machine, the angular position, frequency, and screen mesh size are set once and kept running for years until failure (Steyn 1995). The linear vibratory screening machine has the major concern of screen clogging and reduced efficiency. Screen clogging occurs due to the presence of near-size particles and the moisture content of the material (Rotich et al. 2013; Markauskas et al. 2019). Screen clogging leads to the inefficient passage of particles and misplacement of fine particles with coarse particles discharged from the screen deck (Rotich et al. 2017; Cleary et al. 2018).

1.3 The need for dry processing

The need to utilise the circular motion of the screen can be seen in the work of Dong et al. 2013. The work consists of the development of a DEM model for the various vibrating modes of the screening, such as linear and circular vibration of the screen. It was found that the travel velocity of particles on the screen was higher for the linear vibration and lower for the circular vibration. From the wide range of studies conducted by various researchers, such as Feller et al. 1986 and Dong et al. 2013, it is clear that screen clogging can be tackled using circular vibration in the vibratory screening machine. The major problems of the existing linear vibratory screening machine are the reduced efficiency caused by the screen clogging, high velocity, reduced residence time, and inflexibility in changing the angular position and frequency of the screen.

Due to these problems with the existing linear vibratory screening machine, the production has to be stopped to clear the material clogged on the screen mesh with a wire brush. But as the moisture of the feed material increases, the machine's stoppage is higher, resulting in lower screening efficiency, an increased production cost, and reduced utilisation of high-grade minerals in finer size fractions.

In a linear screening machine, it is also reported that the near-size fine particle was present from the feed end to the discharge end (Hailin et al. 2013). The presence of near-size particles from the feed end will cause the screen blinding from the feed end to the screen's discharge end, which will reduce the screening efficiency. In the circular screening machine, the near-sized fine particles are accumulated only at the discharge end of the screen, reducing screen blinding and increasing screening efficiency. Feller et al. 1986 suggested incorporating two forces, i.e., vertical force and horizontal force, which will reduce screen blinding, and increase screening efficiency. The vertical and horizontal forces will be incorporated into the proposed screening machine.
Some of the other major drawbacks of the existing linear screening machines are the larger number of machine components, leading to larger vibration, and friction (Cady 2010).

1.4 Objectives of the study

In view of the above, there is a need to develop a new type of screening machine which would overcome all the major drawbacks of the existing linear screening machine. Based on the benefits of circular mode of vibration, the present work aims to develop a multifunctional flexible screening machine with a circular mode of vibration. Further, the developed laboratory-scale screening machine is used for the experimental and prediction investigation on the efficiency of screening coal and iron ore with varying moisture content and density. The objectives of the present study are:

1. To conceptualize the design and fabrication of the Flexible screening machine.
2. To study the power consumption and screening performance of coal and iron ore in a flexible screening machine.

3. To study the influential operational parameters such as frequency, angle of inclination, and moisture content on screening using machine learning-based regression and Artificial Neural Network (ANN) modeling.
4. To study the performance of feeding operation utilising the Flexible Screening machine with slight modification.

1.5 Organization of Thesis

The thesis is divided into five chapters. Chapter 1 deals with a brief introduction to vibrating screening machine, and the need for developing a new machine for efficient separation in processing industries. Further, the details of the objectives of the present research work are outlined in this chapter. In Chapter 2, a comprehensive literature review has been carried out regarding the previous studies in the area of vibrating screening, the configuration of the screen, components required, machine learning-based regression and ANN, mathematical optimisation based on Taguchi L27, and fractional factorial DOE technique. Details of the methodology are discussed in chapter 3. The methodology describes conceptual design and fabrication of the new vibrating screen, sample preparation, experimentation, machine learning predictive modeling, and mathematical optimisation techniques. Chapter 4 presents a detailed discussion of results and observations of the performance of the developed vibrating screening machine and its statistical prediction using mathematical modeling. Chapter 5 presents the conclusions drawn based on the investigations, and recommendations for future studies.

CHAPTER 2

2. LITERATURE REVIEW

This chapter deals with a detailed literature study based on many categories covering all the aspects required for the conceptual design, fabrication, and experimentation of vibrating screening machines, along with machine learning predictive modeling and mathematical optimisation of material processing equipment.

2.1 Basics of screening and screening efficiency

Victor et al. 1998 theoretically studied the screening efficiency with respect to the screen slot size, particle size, and time length of screening. Soldinger 1999 utilised a flow model to determine the interrelation, stratification, and particle passage through the screen aperture. Soldinger 2000 utilised a flow model to study the influence of particle size distribution, feed rate, and bed thickness on the stratification and particle passage through the screen aperture. Andrzej et al. 2007 developed a system for controlling the screening efficiency of screening machines. The authors noticed that the constant feeding rate and the percentage of particles passing during the operation need to be maintained for an efficient screening process. Jianzhang et al. 2013 studied the particle screening efficiency for the various effects of vibration parameters such as frequency and swing declination angle. Zhao et al. 2017 studied the circularly vibratory screening machine performance index, such as screening efficiency and throughput capacity, by considering the effects of the screen deck's amplitude, frequency, and inclination angle. Ramatsetse et al. 2017 analysed the frequent failure occurrence in the screening machine.

Zhao et al. 2021 studied the particle distribution during the screening of solid particles in a vibrating screening machine. Further, the simulation performance of particle distribution using the discrete element method was compared with the biological neural network approach. From the result, it was clear that the discrete element method correlated well with the biological neural network approach. Zhang et al. 2021 investigated the low efficiency and easy screen clogging of the vibrating screening machine. The author has also investigated the dynamic analysis of the various design aspect of the vibrating screening machine. Wei et al. 2022 studied the design parameter of the vibrating screening machine for screening powdered material. The authors studied the structural and fatigue strength of the vibrating screening machine. Wang et al. 2021 studied the development of a vibrating screening machine. The authors suggested the importance of the vibration screening machine for coal dewatering and processing for the removal of impurities. It was also suggested that there is more scope to develop the vibrating machine further with different configurations and motions.

Pan et al., 2022 studied the process enhancement of the vibrating screening machine for tailing screening. The authors studied the effects of elastic deformation on the screening clogging of the vibrating screening machine. Xu et al. 2022 investigated the numerical modeling of the thick material layer working condition on the screening performance of the vibrating screening machine. The mathematical modeling provided an accurate relationship between the screening efficiency and vibration parameters. Moraes et al. 2022 studied the high-frequency vibrating screening machine with a thin material layer with continuous feeding conditions. The authors studied the effect of feed rate and screen aperture on the screening performance of the vibrating screening machine.

2.2 Different configurations and motion of vibrating screening machine

William et al. 1994 developed a gyratory screening machine with the increase in the deck's relative movement and improved efficiency. The gyratory screening machine is provided with elliptical motion at its center of gravity. Young et al. 2000 developed a recessed vibrator for providing elliptical motion to the screening machine. Several other authors, such as Roger et al. 2002; Sung et al. 2002; James 2004 have done significant work on providing elliptical motion to the screening machine.

Nigel 2005 developed a screen deck assembly system for the vibratory screening machine. Carr 2011 developed an independent screening machine deck assembly comprising at least one positive displacement mechanism and a hinge point about which angle of inclination ‘α’ was provided to the screening machine deck. The range of angle of inclination ‘α’ provided to the screening machine is ± 5 degrees, ± 15 degrees, and ± 30 degrees. The author described that the material flow rate on the screening machine deck could be varied by varying the angle of inclination ‘α’ and also the screening machine deck direction, i.e., upward direction (for example, -30 degrees) or downward direction (for example, +30 degrees). Several others, such as Schirm 2013; 2015; Sergio 2010; 2011; Zhang et al. 2015, have done significant work in developing different configurations of a screening machine.

A special configuration of the screening machine was developed by Gabriel et al. 1996; the authors utilised a vibratory and a screw feeder for the precision of dosing of powder material such as sand (fine and coarse), seed, fiberglass, cement, and zeolite. Right 2012 developed a screening machine with an adjustable angle feeder. The screening machine consists of a vibration force adjustment and a front bracket with a pin and holes at various angles.

Feliks et al. 2021 studied the rectilinear motion of the vibrating screening machine performance. The experimentation was carried out for different frequencies and amplitudes. The results clearly showed that the rectilinear has not improved the screening performance but reduced power requirement. Yu, Geng, and Wang 2021 studied the screening performance of a flip-flow vibrating screening machine. The experimentation was carried out on the moist particles to determine the effect of screening clogging in the vibrating screening machine. It was observed that the screening efficiency was reduced due to the higher clogging.

Further, there was an improvement in screening efficiency with an increase in the screen length. Li et al. 2021 studied the screening performance of an independent linear vibrating screening machine. The simulation analysis was carried out using the discrete element method, and optimized condition for the operating parameters such as frequency and angle was obtained. Duan et al. 2021 studied the screening performance of the variable elliptical vibrating screening machine. The author studied the material kinetics on the screen deck during the screening process. It was observed that the vibrating screening machine was providing an equal distribution of excitation with reduced power requirement.

Chen et al., 2022 studied the screening performance of the elliptical vibrating screening machine using the discrete element method. The authors have studied the screening performance of the vibrating screening machine for the variation in the material feeding speed. Further, the optimized vibration parameter was provided for the improved performance of the screening machine. Huang et al. 2022 studied the screening performance of a banana-type vibrating screening machine based on the signal analysis. The author correlated the amplitude and energy percentage with the wavelet frequency spectrum.

2.3 Components of the vibrating screening machine

William 1981 developed an improved seal between the hopper and the vibratory box. Johnson and Ronald 2006 developed a support frame for screening assembly. The authors suggested that the support frame facilitates easy and rapid removal of the screen panel. The authors also suggested that the reduction in downtime of the screen deck and improved efficiency could be obtained from the installation of the support frame. Anthony 2007 developed a system to detect the breakage of the porous element of a screen system and process. Nigel 2009 developed a snap-fit fastening arrangement for fixing the screen panel.

Carr et al. 2010 developed a screen clamp that can be attached with sealing elements such as chemical adhesive, mechanical fasteners, or any other method. Robert 2010 developed a mechanism for securing the screen modules. Cady 2010 developed a screen for a vibratory screening machine. The screen is secured with the wedge-like screen frame without bolts, clamps, or additional components, reducing the number of components and the risk of accidental damage. Guozhen et al. 2011 developed a motor and a motor group for the screening machine to balance the control between the larger vibrating force and the mass of the vibrator. Wu et al. 2013 developed a control system for the screening machine to screen the solid phase composition from the slurry.

Xia et al. 2021 investigated the mathematical modeling of the screening efficiency with respect to the screen surface load. The authors have provided the optimized condition of screen loading for the increased screening efficiency of the vibrating screening machine. Zhou et al. 2021 studied the dynamic characteristics of the supporting spring system in a vibrating screening machine. The vibrating screening machine was modified by incorporating higher amplitude and a new leaf spring. From the results, it was clear that the vibrating screening machine produced higher screening performance. Gursky et al. 2022 investigated the design parameters of the flexible screening machine with two motor inertial vibrators. Further, the mathematical and dynamic model was developed to study the performance of the vibrating screening machine. It was further suggested that the vibrating screening machine could be operated for a different range of frequencies.

Ogonowski and Krauze 2022 studied the performance of magnetorheological damper in the screen suspension of the vibrating screening machine. It was observed that the screening performance of the vibrating screening machine was improved due to the additional excitation provided by the magnetorheological damper. Yu et al. 2022 studied the particle flow behavior of the elastic sieve on the screening performance of the vibrating screening machine. The discrete element method showed the particles' kinematics for the amplitude variation of the vibrating screening machine.

2.4 Basics of feeding machine

Lee, Choi, and Paek 2011 investigated the numerical modeling of the dry feeding of the coal gasifier process. The optimal model was developed with accurate physical and chemical boundary conditions. Abbasi, Ege, and Lasa 2011 studied the feeding section of a coal gasifier using a computational particle fluid dynamic model. The developed model provided an accurate demonstration of feeding operation for the rich ash recycled feeds. Alfredas et al. 2012 developed a feeding device to feed cement slurry to develop structural cement panels. The feeding device uses the vibration of the angular headbox for the effective delivery of the cementitious slurry. Kirby et al. 2012 developed a feeding machine for the products such as tablets capsule into a blister pack.

Walter et al. 2012 developed a feeding device for the metered delivery of powdered material. The feeding device was used to improve the feeding of materials to the downstream processing device. Duan et al. 2012 studied the fly ash recirculation to the boiler using bottom-feeding process. The study was carried out to obtain the optimized condition of feeding, which increased the combustion efficiency to 90% and reduced pollutant emissions.

Ma et al. 2015 studied the particle size distribution of the coal feeding. The study investigated the effects of solid concentration on the variation in coal feed rate for the boiler application. The authors also obtained the optimized condition of feed rate for boiler efficiency. Tiziano 2015 developed metal wires feeding device which works at a constant tension. The developed feeding device was found to be highly dynamic, and optimal performance of the feeder was obtained. Rowan et al. 2016 developed a feeding device used for the first and the second flow of material inside the crusher. The feed angle was varied from 35˚ to 70˚ to get effective flow depending on the feed material. Gordian et al. 2017 developed a feeding and discharging device. The device was used for feeding and discharging of the workpiece, such as wood and plastic materials.

Lian, Zhong, and Liu 2021 investigated the discrete element model of the screw feeding process of coal. The authors reported the effects of federate, feeding ratio, and feeding speed on the stability of coal feeding. From the results, it was found that the feeding speed has a higher significance on the stability of the coal feeding process. The major drawbacks of the screening and feeding machine are the usage of many components, which increase the machine's cost, weight, and maintenance. The flexible screening machine will have a reduced number of components, leading to reduced cost, weight, and maintenance of the machine. If the machine works as expected, there will be a significant breakthrough in screening and feeding.

2.5 Machine learning-based regression on material processing

Issahary and Pelly 1981 studied phosphate beneficiation using the calcination process. The authors have developed an accurate regression analysis correlating well with the experimental results. Qingru et al. 2005 predicted the performance of the fluidized bed for coal processing using regression modeling. Results showed that the prediction value of the drag coefficient was in close relation with the experimental value. Rao and Gopalkrishna 2009 studied the grindability index prediction model using the support vector regression model. Results showed that the regression modeling technique provided an accurate nonlinear mathematical relationship between the proximate analysis of coal with the grindability index. Sabah and Koltka 2014 studied the separation performance of lignite coal beneficiation using knelson concentrator. The authors developed a valid regression model for the accurate prediction of experimental results.

Xuliang et al. 2015 studied the performance of processing coal in the bed separator using regression modeling. Results showed that regression modeling was found to be a significant method for predicting separator performance. Yang et al. 2016 predicted the performance of separation characteristics using regression. The influence of hardness and impact velocity on coal crushing was studied. Results showed that the developed mathematical relationship was found to be accurate for prediction.

Lu et al. 2016 studied the performance of coal beneficiation of cyclone and screen using regression. The operational parameters considered were vortex diameter, length, and spigot diameter. Results showed that the regression model on yield and ash content showed good predictions of the results. Onifade et al. 2019 studied the proximate analysis of solid fuel for predicting the performance of gross calorific value using regression. The R-squared value obtained was about 99%, showing a higher correlation between predicted and experimental values.

Özbakir, Koltka, and Sabah 2019 regression prediction modeling of coal beneficiation using hydro cyclone and gravity separation. The results showed a valid correlation of the regression model with the experimental results. Rao et al. 2020 studied the regression prediction modeling of spiral concentration of iron ore. The operational parameters considered for the investigation were feed rate, solid concentration, and splitter position. The response parameters considered in the study were yield and grade. The results clearly showed that the developed regression model correlated well with the experimental results. Aladejare, Onifade, and Lawal 2020 studied the performance of the heating value of fuel using regression and a neural network model. The proximate and ultimate analysis results were used to study the performance. Results showed that the neural network model has better prediction performance than regression.

2.6 Machine learning-based artificial neural network (ANN) on material processing

Kalyani et al. 2008 predicted the performance of cyclones using neural network modeling. The operational parameters selected were cyclone length and solid concentration. The response parameters selected were yield and ash content. Results showed that the prediction value was in close relation with the experimental value. Panda et al. 2012 studied the performance of processing coal in the jig using a neural network. The operational parameters selected were bed material size, feed, and water rate. A backpropagation algorithm was used for the generation of the model. Results showed that neural network modeling was found to be a significant method for predicting jig performance.

Lopamudra and Kumar 2014 studied the performance of gravity concentrators using neural network modeling. The operational parameters selected were the angle, flow, and feed rate. The response parameters selected were grade and recovery. Results showed that the prediction value was in good agreement with the experimental value. Sahu, Chaurasia, and Suresh 2019 studied the performance of processing crushed coal in cyclones using a neural network model. The operational parameters selected were diameter and density. The response parameters selected were yield and coal quality. Results showed that neural network modeling is a highly accurate method of prediction. Jorjani et al. 2009 compared the performance of regression and neural network modeling for predicting the performance of froth flotation using coal. The R-squared value of regression and neural network modeling obtained was 80% and 95.5%, respectively. Results show that the performance of the neural network was better than regression modeling.

Raguraman, Ragupathy, and Sivakumar 2013 studied the performance of the heat transfer coefficient of coal gasification using regression and a neural network model. The experimental results were compared with the prediction results of regression and neural network model. The performance of the neural network was found to be better than that of regression. Panda et al. 2014 assessed the selective flocculation of hematite and kaolinite using a neural network prediction model. The authors utilised different mixing ratios of hematite and kaolinite. The results clearly showed that the neural network model has a better correlation to predicting the experimental separation efficiency.

Ding et al. 2015 studied machine learning-based multiple neural network model prediction analysis on the iron ore beneficiation processing. The operational and response parameters utilised in the present study were performance indices and global production index. Results showed that the neural network model correlated well with the practical industrial process. Wang et al. 2017 studied the optimization algorithm for the mathematical modeling of the beneficiation process. The mathematical modeling results of the developed model were in better agreement with the experimental results.

Yang and Ding 2019 studied the multi-objective evolutionary optimization algorithm of the beneficiation process. The statistical results showed that the developed model was accurate and correlated well with the real-world optimization problem. Tripathy, Mohanty, and Filippov 2020 studied the neural network prediction modeling of the magnetic separation process of low-grade iron ore. The operational parameters considered for the investigation were speed, current, size fraction, and feed rate. The response parameter considered in the study was separation performance. From the results, it was clear that the feedforward neural network model provided a higher R^2

value of 95%. Results also showed that the speed was more sensitive to the separation performance.

2.7 Taguchi L27 Design of Experiments (DOE) on material processing

Sung and Parekh 1996 investigated the operational parameters of fine water dewatering. The authors have utilised Taguchi's mental design to determine the optimized condition for improving the dewatering process. Vathavooran et al. 2006 assessed the performance of fine coal dewatering using the froth image technique. The performance of dewatering was improved by optimizing the operational parameters using Taguchi experimental design technique. Pecina et al. 2014 utilised the Taguchi L4 technique to optimize the leaching process's two operational parameters with two levels. This technique has provided the optimal combination for improving the performance of the leaching process.

Samanta, Samanta, and Sarkar 2003 explored the reliability of the complex system of automation using a factorial DOE model. The study involved the evaluation of individual component's reliability which led to the investigation of the entire complex system and design configuration. Further, it was suggested that the full factorial design modeling is an effective tool for evaluating system reliability. Lee, Bhatia, and Mohamed 2006 evaluated the performance of flue gas desulfurization using a factorial DOE model. The input parameters considered for the study were the effects of the hydration period, the ratio of CaO to fly ash, and the amount of $CaSO_4$. Results provided the optimum experimental condition for maximizing the surface area of the sorbent. Uçurum et al. 2010 studied the flotation to separate unburnt carbon from power plants using a factorial DOE model. The input parameters considered were the percentage of sodium silicate, butanol, kerosene oil, and pine oil. The study involved evaluating the separation performance of unburnt carbon using interaction effects, which showed the effects of each input parameter on the response parameter.

Njoya and Hajjaji 2014 utilised the factorial DOE model to evaluate vitrified ceramic's microstructural and manufacturing properties. The input parameters considered were feldspar content, firing temperature, and soaking time which was investigated by X-ray diffraction and scanning electron microscope. From the results, it was clear that the temperature was found to be the most influential parameter than the effects of the flux content and soaking time. Temel and Majumder 2016 investigated the flotation of cleaning lignite using factorial DOE model. The input parameters considered for the study were the effects of solid concentration, stirring time, collector amount, frother amount, pH, and speed. The response parameter considered was the effectiveness of desliming and flotation. Results showed the optimum experimental condition for obtaining the higher flotation performance. Azimi et al., 2017 studied the performance of a coal separation in a fluidized bed separator using the factorial DOE model. The input parameters considered for the study were the effects of air velocity, bed length, and bed height. The response parameter considered was separation efficiency. Results showed that the bed length was more influential than the effects of the air velocity and bed height.

Hembrom and Suresh 2018 evaluated the performance of the cyclone for coal separation using a factorial DOE model. The input parameters considered for the study were the effects of vortex length, vortex diameter, and spigot diameter. The response parameter considered was % yield and ash. Results showed that the vortex length was the most influential parameter on % yield and ash than the effects of the vortex diameter and spigot diameter. Oluklulu and Koca 2018 developed a factorial DOE model for the gravity separator for cleaning lignite. The input parameters considered for the study were the effects of shake amplitude, frequency, drum speed, and a solid ratio of the separator. The response parameter considered was ash content and combustible recovery. Results showed that the drum speed was the most influential parameter than other parameters. Kechagias et al. 2019 investigated the machinability performance of turning titanium alloy using factorial DOE model. The input parameters considered for the study were the effects of spindle speed, feed rate, and depth of cut. The response parameter considered was cutting force and surface roughness. Results showed that the feed rate was the most influential parameter than other parameters such as spindle speed and depth of cut. It was also suggested that the experimental design provide an appropriate solution for analysing complex experimental conditions.

Kumar and Venugopal (2017) developed an experimental design required for the optimisation of the coal jigging process using Taguchi techniques. The authors have effectively investigated the influence of operational parameters on the jigging process using the Taguchi technique. Bu et al. (2019) have studied the influence of particle size, ball diameter, design, and milling time of the wet ball mill process using the Taguchi technique. This approach has shown the optimized condition of operational parameters, which has improved the milling efficiency of the ball mill. Singh et al. (2020) have optimized operational parameters of transporting coal and ash slurry influencing erosion wear in steel pipelines using Taguchi's experimental design. It was found from the optimisation that the coal shape and size have a major influence in increasing the erosion wear in steel pipelines.

Maharana and Suresh (2020) have studied the influence of a water-only cyclone's optimized operational parameters using the Taguchi technique. The confirmation test on the optimized operational parameters has provided high efficiency of the cyclone process, showing its improved performance using the Taguchi technique. The literature showed that the Taguchi Design of Experiments technique had not been used to study the screening performance of coal and iron ore in the vibrating screening machine.

2.8 Fractional factorial Design of Experiments (DOE) on material processing

Tan et al. (2012) have utilised a fractional factorial Design of Experiments to evaluate significant and insignificant operational parameters for the decolorization of solution during the adsorption process. The operational parameters selected for evaluation were pH, processing time, adsorbent dosage, and temperature. The results showed that the adsorbent dosage was a significant operational parameter compared to the pH, processing time, and temperature. The authors also suggested that the fractional factorial design can reduce the experimental run and resources. Kazemi-Beydokhti, Namaghi, and Heris (2013) experimentally investigated the thermal conductivity of nanofluids using a fractional factorial Design of Experiments. For the investigation, the operational parameters considered were density, temperature, concentration, particle dimension, pH, elapsed, and sonication time. The results showed that the temperature was the most significant operational parameter compared with the other operational parameters. Further, the authors recommended that the developed model be highly predictable and close to the experimental results.

Miller and Sitter 2001 demonstrated the various application of Plackett Burman's fractional factorial design. The effective performance of Plackett Burman's fractional factorial design for real and constructed examples was discussed in detail. Vanaja and Shobha Rani et al., 2007 analysed the application of Plackett Burman's fractional factorial design for various research areas. The Design of Experiments provided the required information from a minimum number of experimental trials. The study identified the most influential parameter affecting the performance of the process.

Bouziane et al. 2012 utilised Plackett Burman's fractional factorial design to study the adsorbent potential of the sawdust. The input parameters selected for the design were temperature, pH, type, source, size and quantity of sawdust, contact time, initial concentrations of cadmium, zinc, and salt stirring speed. From the Design of Experiments, the influential parameters affecting the performance of zinc and cadmium were found with a minimum number of experiments. Kenari et al. 2013 studied the effects of parameters to determine the crosslinking dextran microsphere characteristics using Plackett Burman's fractional factorial design of experiment. From the results, it was clear that the dextran concentration was the most influential parameter affecting cross linking performance.

Tripathi, Bhardwaj, and Ghatak 2017 utilised Plackett Burman's fractional factorial design for ozone bleaching of wheat straw soda pulp. The input parameters selected were kappa number, brightness, pH, consistency, viscosity, time, and temperature. Viscosity and brightness of the wheat straw were found to be the most influential parameters for obtaining higher performance. Fang et al., 2017 analysed the reliability of a diamond drill using Plackett Burman's fractional factorial design. Some of the parameters selected were Catalyst concentration, Ph value, Ni-diamond composite electroplating time, Thickness-raised Ni electroplating time, supersonic wave thickness-raised Ni electroplating time, Solution temperature, Current density of Ni-diamond composite electroplating, Current density of thickness-raised Ni electroplating, and Current density of supersonic wave thickness-raised Ni electroplating. Solution temperature was the most significant parameter obtained from Plackett Burman's fractional factorial design for the higher performance of diamond drill.

Akbari, Ackah, and Mohanty 2017 studied the coal cleaning performance of air tables using Plackett Burman's fractional factorial design. The input parameters considered in the study were longitudinal deck angle, baffle plate height deck frequency, vibration direction angle, airflow frequency deck lateral angle. From the results, it was clear that the deck vibration frequency, longitudinal deck angle, and vibration direction angle were the most significant parameters that influenced the air table's coal cleaning performance. Thirugnanasambandham et al. 2018 were used to study the effective parameters of biodiesel production using Plackett Burman's fractional factorial design. The parameters considered were reaction time, catalyst concentration, molar ratio, moisture level, temperature, and mixing intensity ultrasound power. The result showed that the Plackett Burman design's effectiveness provides significant parameters for biodiesel production.

Suard, Hostikka, and Baccou (2013) developed the fractional factorial Design of Experiments to evaluate fire models' sensitivity. The operational parameters considered were fuel loss rate, flow rate, radiative quantity, emissivity, conductivity, and heat capacity of the wall. The response parameter considered in the study were wall temperature, oxygen molar quantity, heat flux, and temperature. The results showed that the fuel loss rate was the most significant operational parameter compared with the others. El-Taweel and Haridy (2014) studied the application of fractional Design of Experiments design to investigate the significant and insignificant operational parameters for the electrochemical turning process. Surface finish and dimensional accuracy were considered as the response parameters. The operational parameters considered were wire diameter, speed, distance, electrolyte concentration, feed rate, and voltage. The voltage was the significant operational parameter for obtaining a high response to the electrochemical turning process obtained from the Pareto chart results.

The authors also recommended the fractional factorial design for investigating the significant operational parameter reducing the requirement for high-cost resources.

Chérif et al. (2016) experimentally investigated the effects of the operational parameters on water desalination by dialysis process. For the investigation, the operational parameters considered were flow rate, volume, and concentration. Further, the authors have utilised the Pareto chart, which shows the significance of each operational parameter in the vertical column. The results showed that the flow rate was the most significant operational parameter compared to the other operational parameters. Raman and Klima (2017) developed a fractional factorial Design of Experiments to evaluate the significant and insignificant operational parameters for dewatering coal slurry during the pressure filtration process. The operational parameters selected for evaluation were pH, solid concentration, and pressure. The cake moisture was considered as the response parameter. The results showed that the pH was the significant parameter compared to the other operational parameters, such as solid concentration and pressure. Elemary (2019) studied the application of fractional factorial Design of Experiments for investigating the significant operational parameters of rubber recycling machines. The operational parameters selected for evaluation were scrap tire dimension, power, temperature, and the quantity of vaporized and liquid nitrogen used. The results showed that liquid nitrogen was used as the significant operational parameter for the rubber recycling machine. Further, the author has suggested focussing on the in-depth study of obtained significant operational parameters.

2.9 Summarization

From the literature survey, it was observed that the existing vibrating screening has lower screen efficiency with higher screen clogging. It was found that less research has been carried out on the experimentation of the vibrating screening machine using varying moisture and density conditions. It was also observed that mathematical modeling such as machine learning predictive modeling and mathematical optimisation on separation performance had been studied by fewer researchers. Furthermore, less work was carried out to develop a screening machine that can be operated as a feeding machine. In view of the knowledge gap, the objective of the present work is to assess the performance of the vibratory screening machine using screening coal and iron ore with varying moisture content and density. Furthermore, mathematical modeling of the experimental results of screening coal and iron ore was carried out using predictive modeling and mathematical optimisation on separation performance.

CHAPTER 3

3. METHODOLOGY AND METHODS USED IN THIS RESEARCH WORK

Details of the methodology are discussed in this chapter. The methodology includes conceptual design and fabrication of the new vibrating screening machine, sample preparation, experimentation, machine learning predictive modeling, and mathematical optimisation techniques are discussed.

3.1. Methodology

1. Review on different types of screening and feeding methods was carried out in detail through online journals, thesis, and in case required visiting other reputed research and academic institutions.
2. Collection of samples of coal and iron ore from the field/processing plant in bulk to carry out experiments.
3. The moisture content of the samples was investigated using a moisture content analyser.
4. Conceptual design and fabrication of flexible screening machine on laboratory scale were done with necessary attachment.
5. The power consumption of the Flexible screening machine was evaluated.
6. Trial run experiments were carried out to determine screening efficiency on the materials with different moisture content.
7. The study of influential operational parameters such as frequency, angle of inclination, and moisture content using machine learning-based predictive modeling was carried out.
8. The effect of moisture content and density on the separation performance was also studied for coal and iron ore.
9. Modification of flexible screening machine to feeding machine by replacing the screen with a solid plate and the performance of feeding operation was investigated.

FLOW CHART

Fig. 3.1 shows the flow chart of the steps involved in the optimisation of the screening process

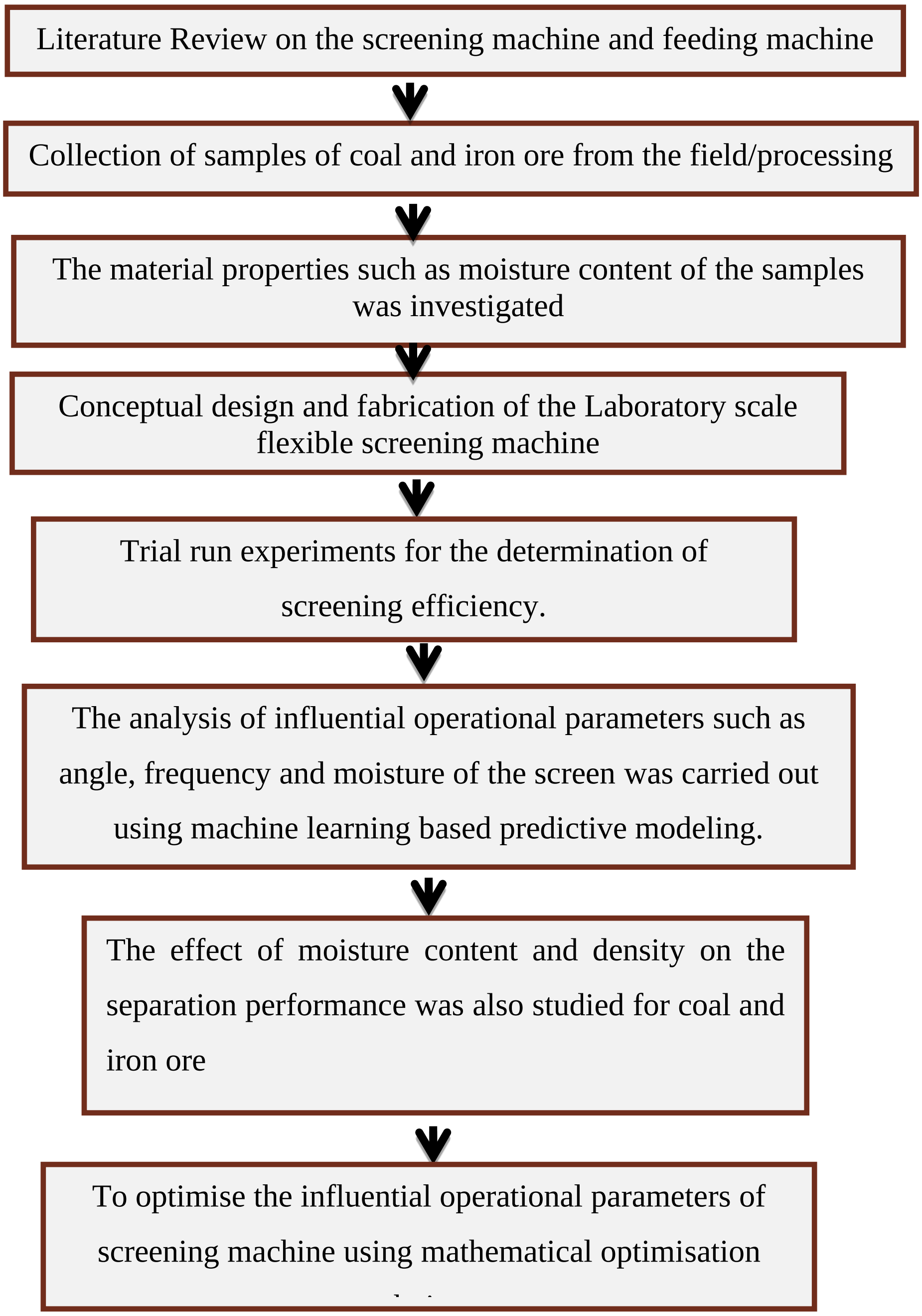


Fig. 3.1. Flow Chart showing the steps involved in the optimisation of the screening process

3.2 Materials used

Coal and iron ore obtained from JSW steel Ltd, Ballari was used as feed material in the present investigation. Both coal and iron ore were extracted in the form of lumps from the mines. The material obtained as lumps consists of various gangue material, which has to be reduced. The size reduction can reduce the gangue material, which also helps in the liberation of high-grade material (Bowman and Bearman., 2014; Rotich et al. 2015; Bowman and Bearman., 2014; Rotich et al., 2015; Hanumanthappa 2020a; Hanumanthappa 2020b; Hanumanthappa 2020c; Harish 2020). One of the major processes considered for producing fine particles is screening (Elskamp et al., 2015; Patra et al., 2016; Tripathy et al., 2016). The screening process is done in various stages, i.e., during extraction, after crushing, and grinding the material. Screening is performed as wet and dry operations. Wet screening has high efficiency, but it utilises more water, which can be avoided by dry screening. Although dry screening has the advantage of preventing water usage, it has reduced efficiency. So, an attempt has been made to increase the efficiency of dry screening using the developed vibratory screen.

Coal beneficiation was carried out to reduce ash content and produce high-grade coal (Chalavadi et al., 2016). It was found from the proximate analysis that coal material of 2 mm consists of 8.72% ash. The total consumption of coal in India was 845.19 million tonnes in 2017, and coal is a prime source of energy for the generation of electricity in the world (Energy Statistics 2018). The reduction in ash content produces high energy-efficient clean coal (Wang et al. 2019). The requirement for a highly efficient vibrating screen has increased with the requirement for clean coal. Coal with an ash content of less than 10% has applications in blast furnaces during iron production.

Similarly, Iron ore beneficiation of size less than 2 mm was carried out to reduce gangue material and produce high-grade material (Gülcan and Gülsoy 2017; Hanumanthappa 2020a; Hanumanthappa 2020b; Harish 2020). So, in the present study, the investigation of efficiency was carried out for screening coal and iron ore of -2 mm+0 mm size fraction from -4 mm +0 mm size fraction using the vibratory screening machine. Although there were several laboratory machines developed for the screening of fine grade particles, such as Hydrosqueeze liberator (Hanumanthappa 2020a, Hanumanthappa 2020b, Hanumanthappa 2020c, Harish 2020), Reflux classifier (Amariei et al., 2014), these machines can separate fine particles, but it utilises a large quantity of water.

So, to avoid the requirement of water, the dry vibratory screening machine was developed. So, in the present study, the experimental assessment on the efficiency of the vibratory screening machine was carried out for screening coal and iron ore with varying moisture content and density. Further, prediction analysis of the experimental results of screening coal and iron ore was carried out using machine learning-based regression and artificial neural network (ANN) modeling techniques.

Table 2.1 Material specification of coal

Volatile Matter (%)	Ash (%)	Fixed Carbon (%)	Carbon (%)	Sulphur (%)	Hydrogen (%)	Nitrogen (%)
22.42	10.11	67.47	80.82	0.41	3.82	1.64

Table 2.2 Material specification of iron ore

Iron (%)	Silicon dioxide (%)	Aluminium trioxide (%)	Loss of Ignition (%)
60.42	5.58	4.03	3.17

Coal and iron ore samples having an average density of 1.32 g/cm^3 and 4.86 g/cm^3, respectively, have been considered in the present investigation. Iron ore is a high-density material compared to coal. The size fraction of coal and iron ore considered in the present investigation was -4 mm + 0 mm. The screening was carried out with a screen mesh of size 2 mm. So, the size fraction of -2 mm + 0 mm undersize is screened off from -4 mm + 0 mm. The selection of the size fraction was made based on its application. The iron ore size fraction of -2 mm+ 0 mm was utilised in making pellets and concrete applications (Silva et al. 2018). -2 mm + 0 mm size fraction of coal is utilised in blast furnace application because of reduced ash content to 8.72%. The initial moisture content of coal and iron ore was 2.45% and 3.94%, respectively. To test the performance of the vibratory screen, the moisture content of each material was varied to 4%, 6%, and 8%. The screening performance of each moisture content of coal and iron ore was reported in the present investigation.

Both coal and iron ore were initially subjected to crushing operation by a roller crusher. After crushing, the sieving is carried out using 4 mm mesh to screen off -4 mm + 0 mm. In the present work, the oversized and undersized particles used to prepare the samples were -4 mm + 2 mm and -2 mm + 0 mm, respectively. So, after obtaining the -4 mm + 0 mm size fraction, sieving was carried out to separate -4 mm + 2 mm and -2 mm + 0 mm size fractions. The feed material was maintained with 70% oversize and 30% undersize particles. In 30% undersized particles, around 10% near sized particles of size fraction -2 mm + 1.70 mm, 15% fine-sized particles of size fraction -1.70 mm + 1 mm, 5% finer sized particles of size fraction -1 mm + 0 mm were maintained. The utilisation of 5% of -1 mm + 0 mm size fraction while preparing the samples was due to the easy material movement through the 2 mm screen mesh (Xiao and Tong 2013). The present work investigates the performance of the vibratory screen with materials close to mesh size.

The feed rate of the material used was 8.33kg/min, i.e., 500 kg/hr. So, the 5.833 kg of oversized material was mixed with 2.5 kg of undersized material for each trial. After mixing the undersize and oversize particles, moisture was added to the sample material and stored at room temperature for 48hours. After storing the material, the moisture content was measured by a Moisture analyser MX-50 (shown in Fig. 3.2). In the present work, a trial and error method to change the moisture content of each sample. The surface moisture of coal and iron ore was varied to 4%, 6%, and 8%.

Fig. 3.2 Moisture analyser MX-50

3.3 Conceptual design and fabrication of the flexible screening machine

In the present work, several attempts were made to study the dry screening performance of the existing vibratory screening machine (Kumar et al. 2018). The linear vibratory screening machine's demerits found were reduced flexibility in varying the angular position, frequency, and screen mesh. In an existing vibratory screening machine, the angular position, frequency, and screen mesh size are set once and kept running for years until its failure (Steyn 1995). The linear vibratory screening machine has the major concern of screen clogging and reduced efficiency. Screen clogging occurs due to the presence of near-size particles and moisture content of the material (Rotich et al. 2013; Markauskas et al. 2019). Screen clogging leads to the inefficient passage of particles and misplacement of fine particles with coarse particles discharged from the screen deck (Rotich et al. 2017; Cleary et al. 2018).

Fig. 3.3 Screen connected to the screen frame with fasteners

Fig. 3.4 Vibrating motor in the conventional vibrating screen

Fig. 3.5 Helical springs attached between the screen frame and base structure

The study of the conventional vibrating screening machine was carried out by visiting the JSW cement plant, Ballari. The vibrating screening machine used in the cement plant was used to screen the cement residues of particle size under 2 mm. The conventional vibrating screen consists of a base, screen, screen frame, two vibrators, and four helical springs. The screen mesh was fixed to the screen frame with fasteners, as shown in Fig. 3.3. The angle of inclination of the screen deck was found to be 7^0 on a downward slope. The vibration to the screen deck was provided by two vibrating motors connected on the two sides of the vibrating screen, as shown in Fig. 3.4. The helical springs were connected between the screen frame and the base structure at the four corners of the vibrating screen, as shown in Fig. 3.5. The fine materials collected from screening were utilised for concrete manufacturing.

Some of the observations made on the shortcomings of the conventional vibrating screen are as follows.

1. The vibrating screen has a larger force of vibration and friction, which causes the wear of the machine parts. The higher friction of the conventional vibrating screen leads to higher power requirements; for instance, in industries, the motor power requirement is around 7.5 kW to 15 kW.

2. The moisture content of the feed materials causes clogging of screen slots which reduces the screening efficiency of the machine. The conventional vibrating screen has a reduced effect on screen clogging because of the type of motion provided to the screen.
3. The vibrating screen will have an isolated system, for instance, in Fig. 3.5, which shows the helical springs used to carry out the load of the vibrating screen. If the isolated system is not perfectly maintained, there will be screen imbalance, loosening of the mechanical fasteners, wear, and fatigue of the machine parts.
4. The vibrating screen requires higher structural strength to withstand the load of the machine parts and vibration.
5. The drawback, such as loosening of the mechanical fasteners, will produce the variable critical frequency of one or more machine components that will vibrate at different strokes compared to the overall machine. The variable critical frequency of one or more machine components will reduce the overall machine life.
6. The vibrating screen has reduced amplitude and stroke length. The higher amplitude and stroke length can throw the material ahead, causing the particle loosening and helping stratification of the material on the screen.
7. The vibrating motion and the downward inclination of the screen will provide less residence time to the feed materials on the screen; thereby, the time required for the particle to pass through the screen aperture will be reduced.
8. The overall screening efficiency in the vibrating screen will be reduced because of a large number of machine parts, a larger force of vibration, friction, wear of the machine parts, overloading, clogging of the screen, and low residence time of the feed material.

Some of the corrective measures need to be considered to overcome the drawback of the conventional screen.

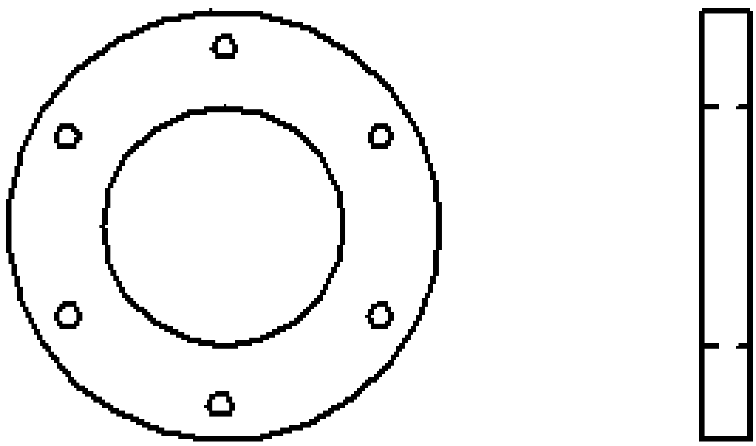
1. The machine should be developed with a reduced number of machine components, thereby reducing the friction and power requirement. The reduction in the number of machine components will avoid the requirement of the higher structural strength of the machine.
2. The reduction in the number of machine components also reduces overall screen load, angular velocities, stress, wear or damage to the screen, screen replacement, downtime, and overall cost of production.
3. The linear vibrating motion of the conventional vibrating screen needs to be replaced with a motion such as circular vibrating motion in such a way that the screening operation can be carried out with reduced blinding of the screen. The circular vibrating motion provided to the screen will provide vertical force to the screen for unclogging of particles from the screen deck.
4. The circular vibrating motion provided to the screen will give a larger amplitude and stroke length of the screen, increasing the stratification of the particles on the screen.
5. The circular vibrating motion provided to the screen will also reduce the velocity of the particles on the screen, increasing the residence time of the feed materials on the screen.
6. The angle of screen inclination can be adjusted, which can also be used to control the residence time of the feed material.

The conceptual design of the flexible screening machine was carried out in the JSW R&D department, and the fabrication was carried out in JSW ISHOP. The conceptual design of the flexible screening machine involved a lot of modifications, and the final conceptual design is presented in this section.

The flexible screening machine was conceptually designed to provide a circular motion to the screen deck. The circular motion provided to the screen deck in an upward direction will reduce the particle velocity and increase the feed material's residence time on the screen deck. The flexible screening machine consists of a reduced number of parts, which reduces friction, thereby reducing power consumption. The flexible screening machine includes two eccentric shafts, bearings, flange, screen deck with holder, screen mesh, and support system.

The step-by-step procedure of conceptual design, fabrication, and assembly of the flexible screening machine was discussed in this section.

The first step was conceptual design and fabrication of the parts required for assembling the flexible screening machine. The flange holds the bearings and also eccentric shafts. The pictorial representation and fabricated part of the flange are shown in Fig. 3.6.



Front view Side view

Fig. 3.6 Front view, side view and fabricated part of the flange

The screen deck was fastened to the screen mesh. The feed material was poured on the screen mesh for separation. The pictorial representation and fabricated part of the screen deck are shown in Fig. 3.7.

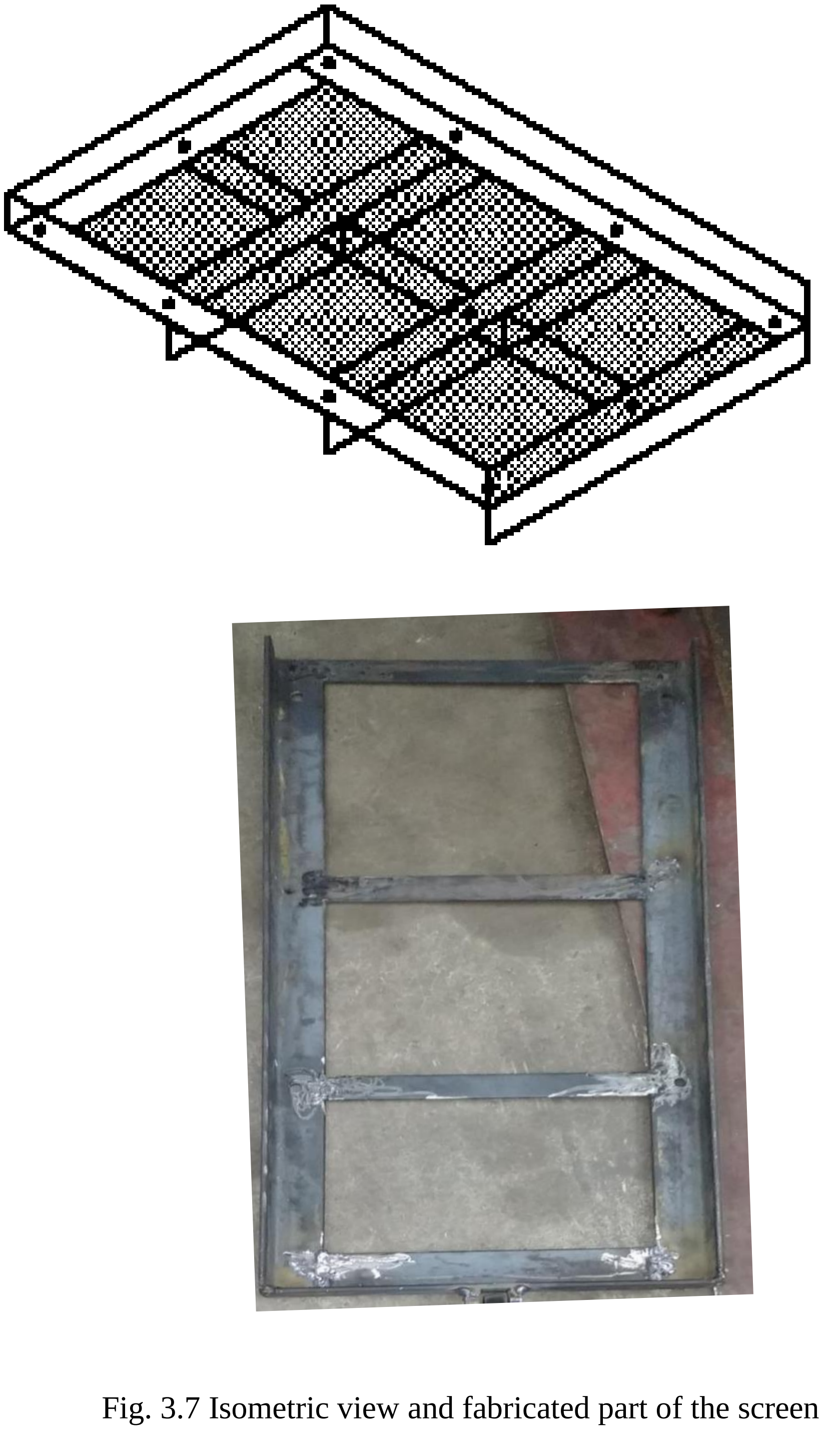


Fig. 3.7 Isometric view and fabricated part of the screen deck

The screen holder holds the screen deck and eccentric shaft. The screen holder was attached to the screen deck at the four corners of the screen deck. The pictorial representation and fabricated part of the screen holder are shown in Fig. 3.8.

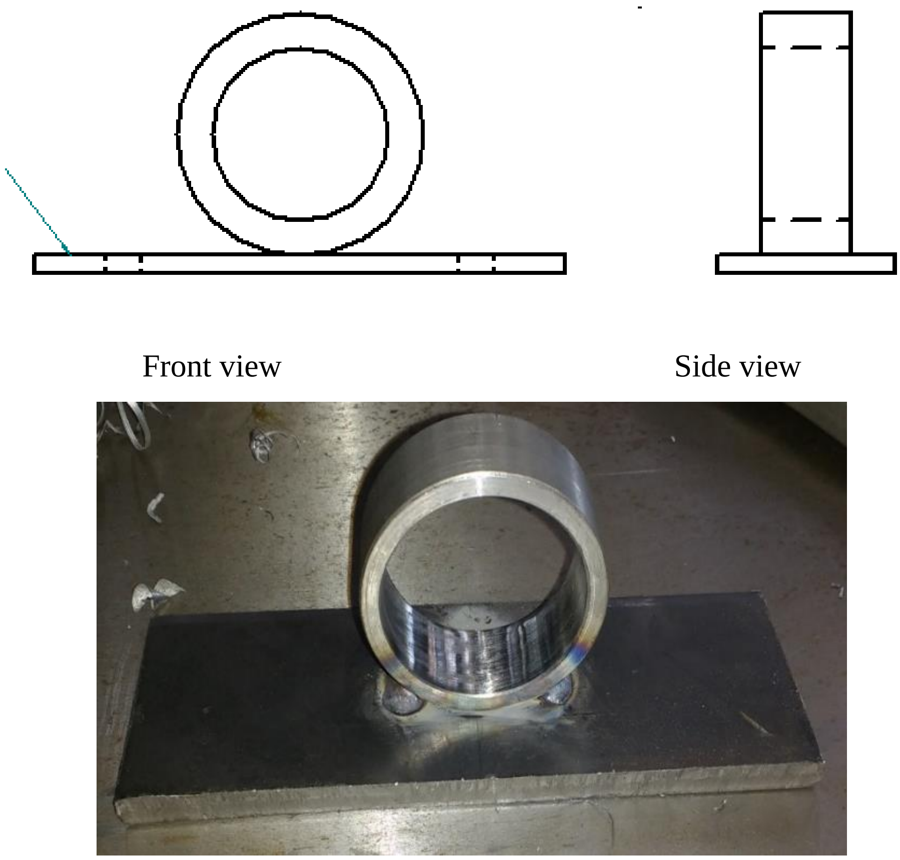


Fig. 3.8 Front view, side view and fabricated part of the screen holder

The eccentric shaft carries the screen deck and transmits the circular motion to the screen. The eccentric shafts were connected to the motors. The pictorial representation and fabricated part of the eccentric shaft are shown in Fig. 3.9.

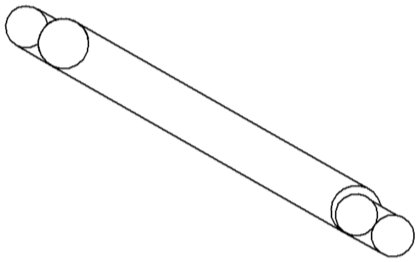


Fig. 3.9 Isometric view and fabricated part of the eccentric shaft

The support system carries the screen deck, eccentric shaft, and screen holder. The support system was connected to the eccentric shaft with the bearing, which transmits the circular motion to the screen deck. The pictorial representation and fabricated part of the support system are shown in Fig. 3.10.

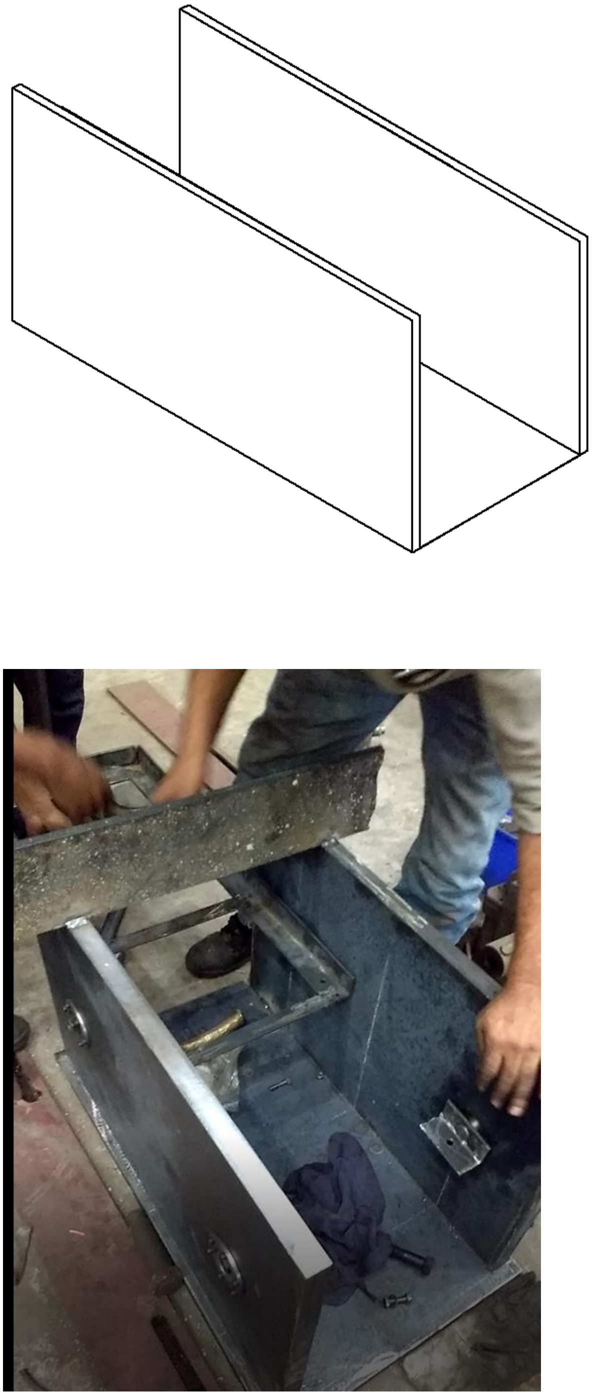


Fig. 3.10 Isometric view and fabricated part of the support system

The first step of the assembly was attaching the flange to the support system, which is shown in Fig. 3.11. The flange is assembled to hold the bearing on the support system.

The flange was to avoid the unwanted movement of the bearing during the motion of the screen deck.

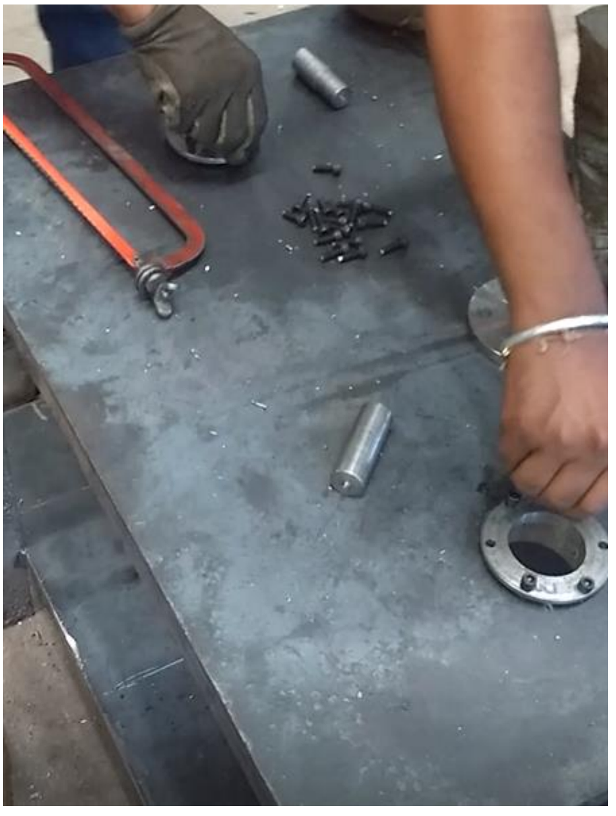


Fig. 3.11 Assembly of the flange on the support system

The second step of the assembly was assembling the eccentric shaft and screen holder on the support system, which is shown in Fig. 3.12 and Fig. 3.13. The two-screen holders were placed on each eccentric shaft. The eccentric shafts were connected to the bearing on four sides, and one end of the shafts was connected to motors. The eccentric shafts provided a circular motion to the screen deck.

Fig. 3.12 Assembly of the shaft with coupling

Fig. 3.13 Assembly of the screen holder on the shafts

The third step of the assembly was attaching the screen deck with the screen holder, which is shown in Fig. 3.14. The screen deck consists of the screen frame and the screen mesh.

Fig. 3.14 Assembly of the screen deck

The fourth step of the assembly was attaching the eccentric shafts to the respective induction motors of power 1.5kW, which is shown in Fig. 3.15.

Fig. 3.15 Assembly of the eccentric shafts to the respective motors

The final assembly drawing and the flexible screening machine assembly are shown in Fig. 3.16 and Fig. 3.17.

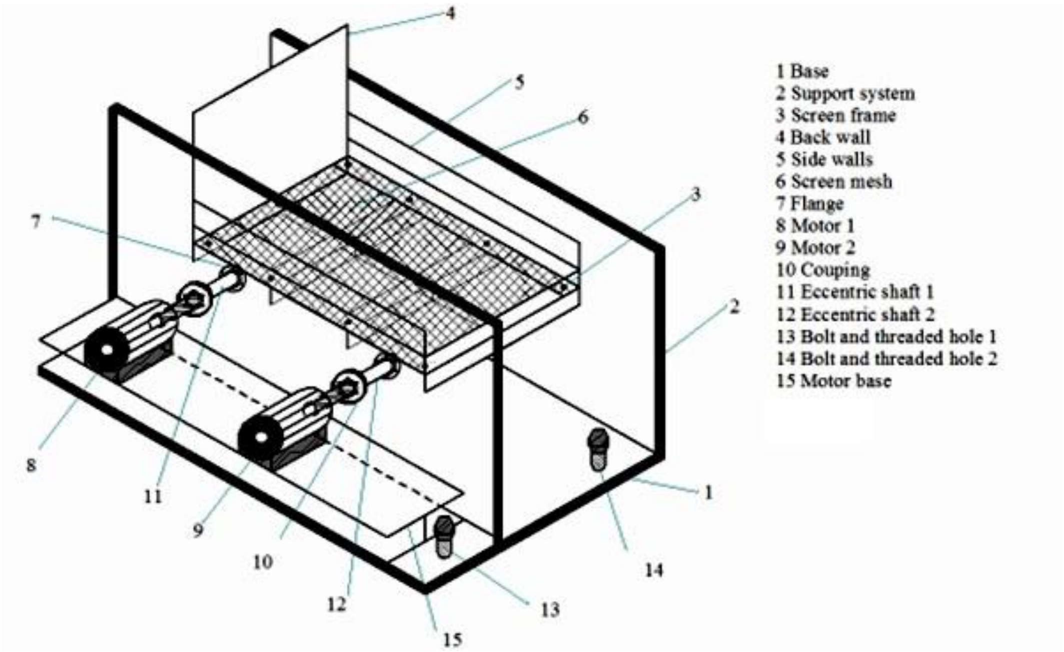


Fig. 3.16 Final assembly drawing of the flexible screening machine

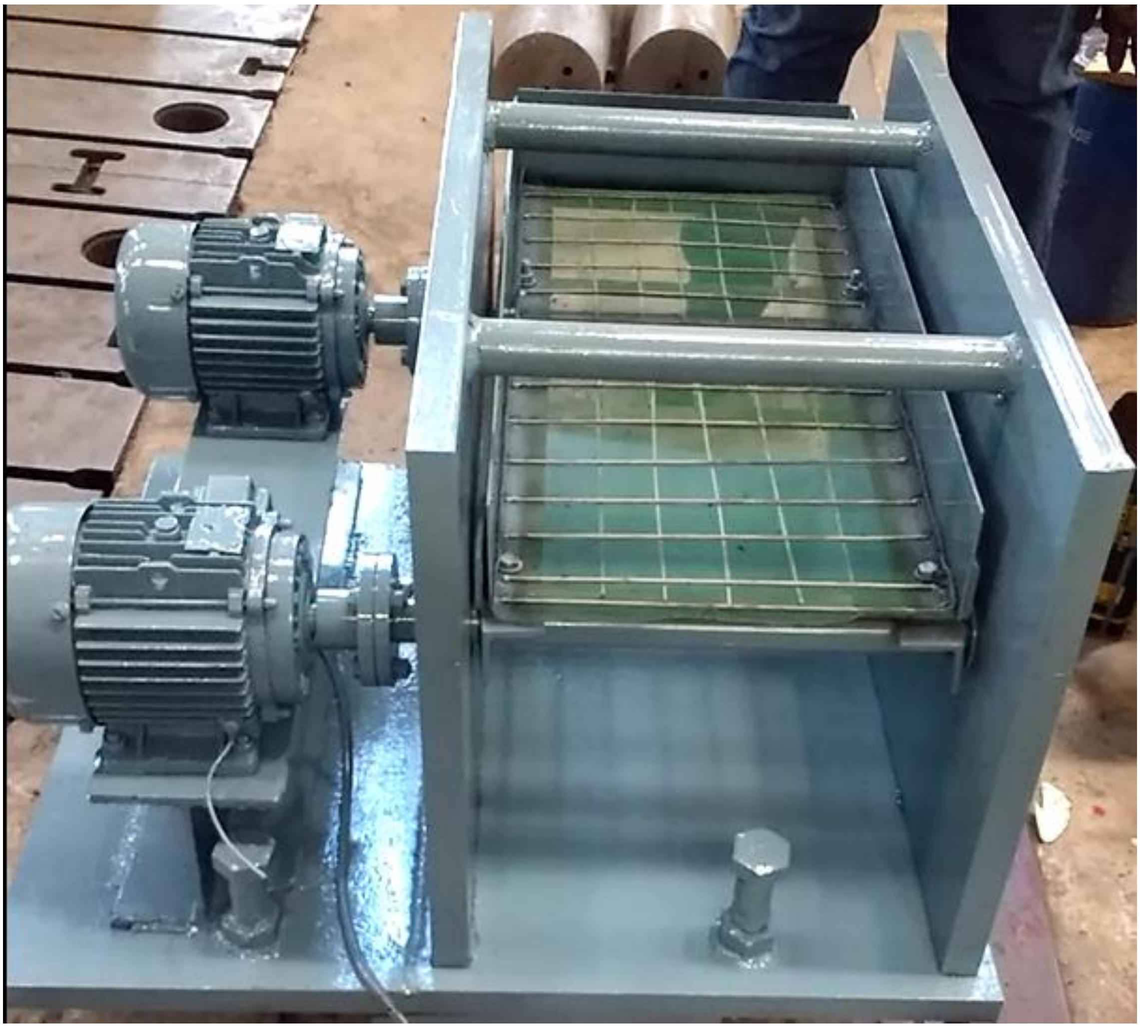


Fig. 3.17 Final assembly of the flexible screening machine

3.4 Power requirement of the flexible screening machine

The power requirement for the screening coal and iron ore in the screening machine was calculated for a maximum frequency of 12Hz considered for the study. The maximum frequency was selected based on trial-and-error method. Further the collision between the particles was higher for screening more the12 Hz with developed machine.
Power (kW) = $2\Pi NT / 60 \times 1000$

N = Speed (Maximum) in rpm = Frequency (Maximum) in Hz X 60

So, Speed (Maximum) in rpm = 12 X 60

Speed (Maximum) in rpm = 720 rpm

Torque (N-m) = Force * Perpendicular distance= 24.5*0.4= 9.9 N-m

Power (kW) = (2Π X 720 X 9.9) / 60 X 1000

Maximum Power (kW) = 0.75 kW

So, the maximum power required for the screening of coal and iron ore in the screening machine required two motors of 0.75 kW.

3.5 Experimentation

The shortcomings of the available screening machine were considered, and a new screening machine was developed. The screening machine used in the present work is shown in Fig. 3.16. The developed screening machine includes motors connected to eccentric shafts, which can provide a circular motion of 5 mm to the screen deck. The width and length of the screen deck were 400 mm and 800 mm, respectively. The effective screen area maintained was 60%. A screen mesh of 2 mm perforation was attached to the screen deck. The developed equipment has flexibility in varying the operational parameters. The operational parameters include the angle of the screen and frequency, which can be modified by angle bolts and frequency drive, respectively.

Before the screening, the angle and frequency were set by adjusting the bolts and frequency drive, respectively. The samples were fed to the screen at a rate of 8.33Kg/min. As the samples reached the screening machine, the sample particles would move in a circular direction on the screen. The motion of the eccentric shafts provided this movement. During the screening, the sample would travel from the feed to the discharge end. As the sample travels on the screen, some undersize would flow through the perforation, and the remaining sample would move to the discharge end. Both the collected samples were weighed, and the screening efficiency was calculated using the undersized weight. The screening efficiency is defined as the ratio of the quantity of the undersize coal recovered to the quantity of the undersize contained in the raw material (Wodzinski et al. 2003).

In the present work, an attempt has been made to evaluate the effect of varying moisture content and density on the separation performance of coal and iron ore in the screening machine. Furthermore, it was observed that fewer works were done on the machine learning-based prediction modeling of screening efficiency. So, statistical prediction and validation were carried out on the experimental results of screening efficiency obtained for coal and iron ore at each moisture condition. The present work was to develop the most suitable mathematical model for predicting the screening efficiency of coal and iron ore in the screening machine.

3.6 Machine learning-based data analysis

From the literature, it was evident that very limited work was carried out by researchers such as Grozubinsky et al. 1998 on the estimation of efficiency of the vibrating screening machine. Furthermore, understanding the screen performance and solving relevant problems are tedious tasks; therefore, it is necessary to utilise numerical and analytical approaches (Zhovtiuk et al. 1988). So, the machine learning-based predictive models, such as regression analysis and artificial neural networks (ANN) model, were utilised to predict efficiency.

In industries, automation and machine learning can be incorporated, which improves the performance of each machine. Machine learning is the field of study that gives computers the ability to learn without being explicitly programmed. So, to study the separation performance of the vibrating screening machine, machine learning-based predictive modeling such as regression and artificial neural network (ANN) modeling techniques were considered. An artificial neural network (ANN) and regression can be utilised to predict the correlation between the operational and response parameters. This technique's prediction can serve as input for the automation system (Panda et al. 2012). Artificial neural network (ANN) and regression are utilised in automation industries to optimize research utilisation, future value prediction, and machine learning (Lopamudra Panda et al. 2012). ANN and regression are powerful methods that can be applied to evaluate the vibrating screen's performance. Prediction using ANN and regression leads to develop the statistical relationship between the operational parameters and response parameters (Jorjani et al. 2009; Jorjani, Mesroghli, and Chehreh Chelgani 2008; Sahu, Chaurasia, and Suresh 2019; Zhou et al. 2016).

The application of the prediction model of machine learning-based regression and ANN has been increasing steadily for solving complex problems and providing a mathematical relationship between the operational and the response parameters data. So, an attempt has been made in the present work to develop a regression and ANN prediction model to predict the performance of the vibrating screening machine for screening coal and iron ore. The development of the machine learning-based prediction model is discussed in detail in this study. The present work will lead to the development of an efficient system to predict the performance of the vibrating screening machine.

For the regression and ANN prediction model development, the screening result data was obtained by a series of tests with coal and iron ore in the vibrating screening machine. During experimentation, the frequency was varied, and the efficiency was obtained. For each angular position and moisture condition of screening coal and iron ore, 33 different trials were carried out. The machine learning-based prediction model was developed with frequency as an operational parameter and efficiency as a response parameter. So, the present work provides the regression and ANN prediction model in terms of frequency for all the angular position and moisture conditions of screening coal and iron ore in the developed vibrating screening machine.

3.6.1 Regression model

Regression model are widely used for predicting and analysing results. Regression modeling develops a mathematical equation for the indirect estimation of output data. The developed mathematical equation simplifies the complexity of the problem. The primary purpose of regression modeling is to develop a relationship between the operational and the response parameters data. In the present work, the mathematical modeling of efficiency for screening coal and iron ore for all the angular and moisture conditions was developed. In industries, the vibrating screening machine was provided with the variation in frequency only. So, the mathematical model was developed for frequency as operational parameter data and efficiency as the response parameter data.

3.6.2 Artificial neural network model

Artificial neural network modeling provides the prediction of the output data using a nonlinear mathematical equation. The artificial neural network (ANN) model consists of three layers, i.e., input layer, hidden layer, and output layer, as shown in Fig. 3.15. Similar to regression modeling, the mathematical model was developed for frequency as the operational parameter data and efficiency as the response parameter data. A feedforward backpropagation technique was used for ANN modeling. This technique allows the model to adjust the weights in such a way that the error decreases with each iteration. Out of 33 experimental results, approximately 70% (23 results) were used for training, and the remaining 30% (10 results) were used for testing and validation of the ANN model (Kumar et al. 2013).

The performance validation of the ANN model is not required as the model provides both validation and prediction results. After the regression model and ANN model's prediction results were obtained, a comparative study using the residual analysis was carried out to evaluate the most efficient modeling technique for predicting the screen performance of coal and iron ore in the vibrating screening machine.

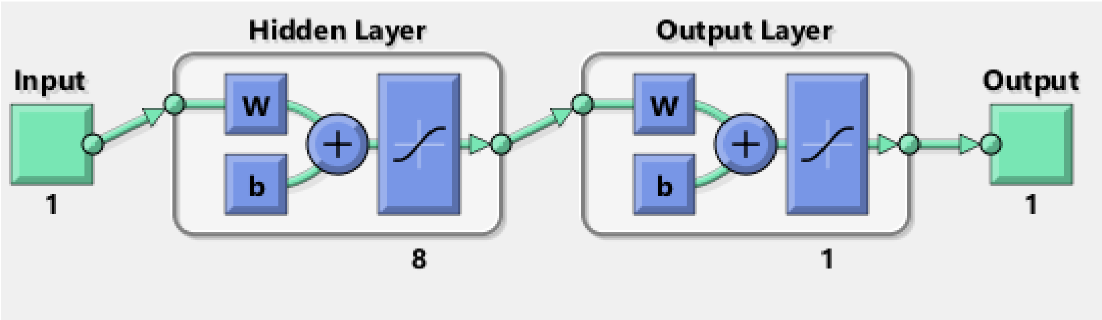


Fig. 3.15 Artificial neural network model

After developing the prediction model, regression and ANN model verification and validation were carried out on the developed optimal model. In the present work, the model was validated using residuals obtained from each regression and ANN model. The residuals are the difference between experimental and predicted values. The machine learning-based prediction model's accuracy was evaluated using four different conditions, i.e., independence, homoscedasticity, normality, and standard deviation. In the present work, the residual analysis was carried out using a normal probability plot and histogram. Probability plots and histograms were plotted for the residuals of the regression and ANN model. The probability plot with the residual near the normality line's random distribution shows that the model fits well with the experimental data. The residual analysis verifies the accuracy and validation of the developed prediction model.

3.7. Statistical optimisation

In the present work, Taguchi L27 and the Fractional factorial Design of Experiments (DOE) were carried out to investigate the optimal condition of operational parameters for screening coal and iron ore in the developed vibrating screening machine. The optimisation analysis on the experimental results of screening coal and iron ore was carried out using the Taguchi L27 technique. Additionally, significant operational parameters were obtained for screening coal and iron ore using fractional factorial analysis. In the present study, the screening machine's performance was evaluated using the Design of Experiments (DOE). The DOE evaluation provides the effects of operational parameters, such as moisture content, angle, and frequency, on the response parameter, i.e., separation efficiency.

Design of Experiments (DOE) is an organized technique for evaluating the statistical relation between the operational and response parameters. DOE provides a statistical experimental design to develop the significant operational parameters with the best level set to maximize the response parameter condition. Previously, many research work has carried out a one-factor-at-a-time (OFAT) experimental design for evaluating the performance of each operational parameter individually, which required the highest time and resources for the experimentation. High-resource utilisation was avoided by developing the Taguchi L27 and fractional factorial design to estimate the effects of operational parameters on response parameters simultaneously. The Taguchi L27 and fractional factorial methods are significant methods of DOE, which process systematic design experimental runs with orderly varying operational parameters.

This study presents the application of a Taguchi L27 and fractional factorial design of an experiment for the separation of coal and iron ore in a screening machine. The Taguchi L27 and fractional factorial design of experiments is an important tool utilised for research and development applications. The Taguchi L27 and fractional factorial design of experiments is an efficient tool for evaluating the effect of two or more operational parameters on the response parameter. The Taguchi L27 and fractional factorial design of experiments are applied to new equipment or processes where many operational parameters are more likely to be studied with low resource utilisation. Further, the fractional factorial design provides a significant operational parameter by running a fraction of the Taguchi L27. For the Taguchi, as the number of the factor was increased, the experimental trial runs were more, thereby increasing the time and resources required. So, the fractional factorial design was developed to evaluate the screening machine's performance using minimal resource utilisation.

3.7.1. Taguchi L27 Design of Experiments (DOE) Technique

MINITAB 17 software was used to develop and analyse the Taguchi L27 Design of Experiments (DOE) for evaluation of the screening performance of coal and iron ore in the screening machine. In the present work, three operational parameters such as moisture content, angle, and frequency were utilised to study the response parameter, i.e., screening efficiency of coal and iron ore. In the present work, the maximization of screening efficiency was obtained by selecting the "larger the better" condition. For this condition, Signal-to-noise (S/N) ratio is determined for each experimental trial, reducing the response parameters' noise. For larger the better condition, the S/N ratio is determined for each experimental design combination using equation 3.1.

$$S/N = -10 * \log_{10}(\Sigma(1/Y^2)/n) \qquad \text{------Equation 3.1}$$

where Y = response obtained for each trial and n = number of responses obtained for experimental design.

Table 3.1 shows the Taguchi L27 Design of Experiments (DOE) for evaluating the optimal condition of screening performance of coal and iron ore. After obtaining Taguchi's experimental design, experiments were conducted by varying different operational parameter levels to obtain response parameters, i.e., screening efficiency. Further, the experimental trial's response parameters were utilised to analyse the Taguchi L27 experimental design, and the degree of influence of each operational parameter was obtained from the main effect plot. Furthermore, significant operational parameters were identified using the fractional factorial method for screening coal and iron ore.

Table 3.1 Taguchi L27 Design of Experiments (DOE)

Moisture content (%)	**Angle (degree)**	**Frequency (Hz)**
4	1	6
4	1	9
4	1	12
4	3	6
4	3	9
4	3	12
4	5	6
4	5	9
4	5	12
6	1	6
6	1	9
6	1	12
6	3	6
6	3	9
6	3	12
6	5	6
6	5	9
6	5	12
8	1	6
8	1	9
8	1	12
8	3	6
8	3	9
8	3	12
8	5	6
8	5	9
8	5	12

3.7.2. Fractional factorial Design of Experiments (DOE) Technique

The fractional factorial design has a major objective of evaluating the performance of two or more operational parameters on the response parameter simultaneously. The fractional factorial design provides large data on a significant and insignificant operational parameter with a lesser number of experimental trial runs. The modeling approach, such as factorial design, is an important method that evaluates the significant levels of operational parameters causing the variation in the response parameter and predicts the same with a simplified mathematical equation. The fractional factorial design develops an experimental design to collect the required data for evaluating the performance of operational parameters. The experimental design is developed for the collection of maximum amounts of data with minimal time and resources. Table 3.2 shows the fractional factorial Design of Experiments (DOE) for evaluating the significant operational parameters of screening performance of coal and iron ore. Table 3.2 also shows the reduced experimental trial runs required for the analysis, indicating the minimum resource utilisation.

Table 3.2 Fractional factorial Design of Experiments (DOE)

Moisture content(%)	**Angle (degree)**	**Frequency (Hz)**
4	1	12
8	1	6
4	5	6
8	5	12

The fractional factorial Design of Experiments modeling provides the model fitting for all the operational parameters. The results show the significant and insignificant operational parameters depending upon the hierarchy of model fitting. So, in the present work, the results of fractional factorial design, i.e., Pareto chart, were used to evaluate the optimum level and significant operational parameters.

The Pareto chart provides the effective communication of the experimental results of each operational parameter. The predicted resulting interaction of the operational parameters is arranged from the largest significant value to the smallest significant value. The intensity of each operational parameter is indicated in the column, and the highest line of the column represents a high statistically significant value. So, the present work depicts the application of a machine learning-based regression and ANN prediction modeling and validation of the separation performance of coal and iron ore in a flexible screening machine. Furthermore, the present work also presents the optimal condition of the operational parameters using Taguchi L27 and fractional factorial Design of Experiments (DOE) for the separation of coal and iron ore in a screening machine.

CHAPTER 4

4. RESULTS AND DISCUSSION

This chapter presents a detailed discussion of results and observations of the performance of the developed vibrating screening machine and its statistical prediction using mathematical modeling.

4.1 Effect of screening coal and iron ore at 4% moisture for varying angular position and frequency

Table 4.1. Screen efficiency of coal and iron ore with 4% moisture for different angular conditions.

Frequency of vibration in Hz	Screening efficiency of 4% moisture coal			Screening efficiency of 4% moisture iron ore		
	5^0	**3^0**	**1^0**	**5^0**	**3^0**	**1^0**
4.00	62.15	66.24	79.50	82.43	79.52	79.69
4.25	62.52	66.89	79.77	82.72	79.96	79.80
4.50	62.84	67.43	80.04	83.19	80.64	80.08
4.75	63.23	68.01	80.33	83.46	81.09	80.54
5.00	63.78	68.66	80.55	83.98	81.80	80.92
5.25	63.98	69.17	80.76	84.35	82.36	81.53
5.50	64.26	69.83	80.97	84.81	82.95	81.87
5.75	64.61	70.63	81.16	85.52	83.58	82.16
6.00	64.87	71.58	81.32	86.21	83.94	82.62
6.25	65.14	71.85	81.61	86.90	84.37	83.23
6.50	65.59	72.13	81.99	87.47	84.89	83.71
6.75	66.84	72.34	82.47	88.15	85.32	84.12
7.00	66.35	72.65	82.73	88.97	85.93	84.67
7.25	66.63	73.13	82.95	89.58	86.79	85.17
7.50	66.91	73.61	83.11	90.17	87.59	85.78
7.75	67.17	73.98	83.29	90.79	88.40	86.51
8.00	67.42	74.23	83.42	91.47	89.21	85.73
8.25	67.71	74.41	83.75	92.16	90.13	85.16
8.50	67.93	74.69	83.99	93.01	89.37	84.74
8.75	68.19	74.86	84.16	93.63	88.74	84.19
9.00	68.54	75.12	84.39	94.56	88.06	83.67
9.25	68.89	75.43	84.87	93.99	87.39	83.34
9.50	69.23	75.79	85.12	93.26	86.88	82.84
9.75	69.67	76.33	85.61	92.71	86.14	82.42
10.00	69.92	76.69	85.96	92.04	85.53	81.86
10.25	70.28	77.46	85.19	91.39	84.87	81.14

10.50	70.63	78.03	84.76	90.72	84.23	80.66
10.75	70.96	78.71	83.97	90.13	83.67	80.14
11.00	71.37	78.43	83.23	89.41	83.20	79.55
11.25	71.63	77.94	82.47	88.60	82.81	78.92
11.50	71.15	77.13	81.93	88.13	82.17	78.23
11.75	70.67	76.28	81.21	87.39	81.75	77.69
12.00	69.42	75.36	80.45	86.81	81.22	77.16

Table 4.1 shows the screen efficiency of coal and iron ore with 4% moisture for different angular conditions. Fig. 4.1 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 1 degree and 4% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 79.50%. The efficiency increases significantly (from 79.77% to 85.61%) with an increase in frequency (from 4.25Hz to 9.75Hz). The efficiency value stabilizes around 85.96% at a frequency of 10Hz and decreases to 80.45% at 12Hz. Plotting the test results of efficiency against the frequency of the screen for screening coal shows that the recovery of the undersized coal particles has increased with the increase in frequency. It was observed that as the frequency was increased from the lowest value of 4Hz, the coal particles were obtaining less force of vibration for the passing of undersized coal particles through the screen slots. As the frequency was increased, the coal particles obtained a high force of vibration, causing the undersized coal particles to pass through the screen slots. As the passage of undersized coal particles through screen slots was increased, the efficiency increased to 85.96% at 10Hz.

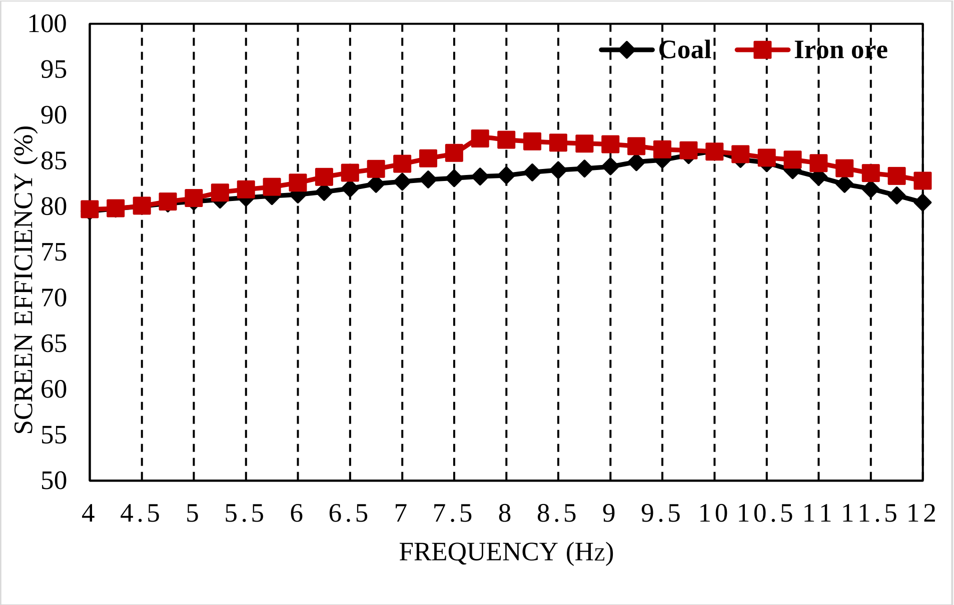


Fig. 4.1 Vibratory screen efficiency of coal and iron ore maintained at 4% moisture and 1^0

Fig. 4.1 also shows the results of screening iron ore; the efficiency obtained at a frequency of 4Hz was 79.69%. The efficiency increases significantly (from 79.80% to 86.88%) with an increase in frequency (from 4.25Hz to 7.50Hz). The efficiency value stabilizes around 87.45% at a frequency of 7.75Hz and decreases to 82.84% at 12Hz. Plotting the test results of the efficiency against the frequency of the screen for screening iron ore shows that the recovery of the iron ore undersized particles has increased with the increase in frequency. It was observed that as the frequency was increased from the lowest value of 4Hz, similar to the undersized coal particles, iron ore feed on the screen deck was obtaining less force of vibration for the passing of iron ore undersized particles through the screen slots. As the frequency was increased, the iron ore undersized particles obtained a high force of vibration, causing less accumulation of iron ore particles near the inlet zone, and also optimal bouncing of iron ore particles was achieved. This has caused a higher residence time of the particles on the screen leading to the high passage of iron ore particles through screen slots and high efficiency of 87.45% (obtained at 7.75Hz). Further increase in the frequency has increased the bouncing of the material, causing the undersize particles not to pass through the screen slots (Harzanagh et al. 2018). So, the efficiency has reduced to 82.84% at 12Hz.

Fig. 4.2 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 3 degrees and 4% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 66.24%. The efficiency increases significantly (from 66.89% to 78.03%) with an increase in frequency (from 4.25Hz to 10.50Hz). The efficiency value stabilizes around 78.71% at a frequency of 10.75Hz and decreases to 75.36% at 12Hz. For screening coal at 3 degrees, the increase in frequency from 4Hz to 10.75Hz has provided an increase in the force of vibration, good particle movement, particle mixing, and particle segregation on the screen deck. Therefore, the efficiency has increased to 78.71%.

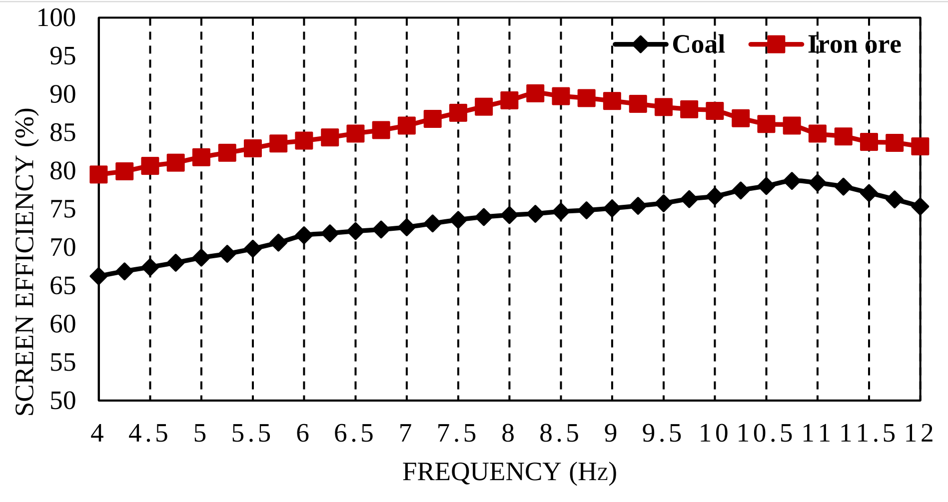


Fig. 4.2 Vibratory screen efficiency of coal and iron ore maintained at 4% moisture and 3^0

Fig. 4.2 also shows the results of screening iron ore, the efficiency obtained at a frequency of 4Hz was 79.52%. The efficiency increases significantly (from 79.96% to 89.21%) with an increase in frequency (from 4.25Hz to 8Hz). The efficiency value stabilizes around 90.13% at a frequency of 8.25Hz and decreases to 83.20% at 12Hz. For screening iron ore at 3 degrees, the particle movement, particle mixing, and segregation were more than the coal; thereby, the passing of iron ore undersized particles through the screen slots was more (Golovanevskiy et al. 2011; Zhao et al. 2019). Therefore, the highest efficiency of 90.13% was obtained for screening iron ore at 3 degrees and 4% moisture conditions.

Fig. 4.3 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 5 degrees and 4% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 62.15%. The efficiency increases significantly (from 62.52% to 71.37%) with an increase in frequency (from 4.25Hz to 11Hz). The efficiency value stabilizes around 71.63% at a frequency of 11.25Hz and decreases to 69.42% at 12Hz. As the angular position of the screen was increased to 5 degrees on an upward slope, the frequency requirement for screening and carrying the coal particles from the inlet to the outlet zone has increased. The increase in the frequency to 11.25Hz was required to obtain a high efficiency of 71.63%. As the frequency increased beyond this optimum value, there was a drop in the particles passing through screen slots and efficiency to 69.42%.

Fig. 4.3 also shows the results of screening iron ore; the efficiency obtained at a frequency of 4Hz was 82.43%. The efficiency increases significantly (from 82.72% to 93.63%) with an increase in frequency (from 4.25Hz to 8.75Hz). The efficiency value stabilizes around 94.56% at a frequency of 9Hz and decreases to 86.81% at 12Hz. For screening of coal and iron ore, it was observed that similar trends of increase in efficiency with an increase in frequency were obtained until an optimal value was reached. The optimal frequency results in clearing screen slots, good particle motion, particle throwing, and particle stratification on the screen deck, providing more underflow particles passing through the screen slots. So, efficiency was highest when the frequency was optimal. However, as the frequency was further increased, the particle-particle vibration and intense bouncing of the particles on the screen were more. Due to this vibration and bouncing, high collision between particles and improper particle stratification occurred on the screen deck; thereby, underflow particles passing through screen slots and efficiency were reduced.

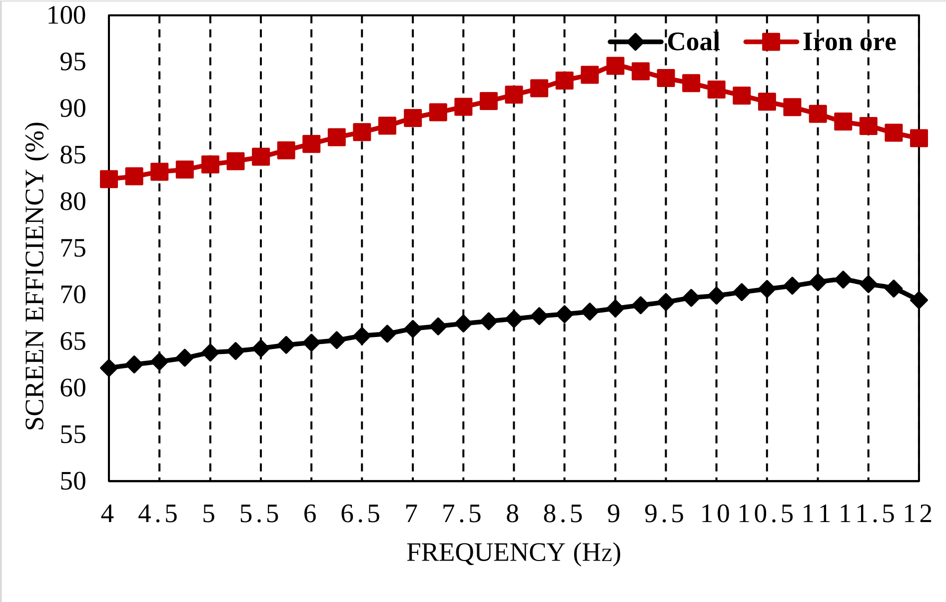


Fig. 4.3 Vibratory screen efficiency of coal and iron ore maintained at 4% moisture and 5^0

From the screening results of coal and iron ore, iron ore particles have the highest efficiency. It was observed that the iron ore particles obtain good rotational motion, particle mixing, particle loosening, and particle stratification on the screen (Golovanevskiy et al. 2011). The highest particle stratification leads to a faster movement of the particles from the top layer of the feed to the bottom layer of the feed and then through the screen slots (Soldinger 1999; Soldinger 2000). The highest value of efficiency of 86.51%, 90.13%, and 94.56% was obtained at a frequency of 7.75Hz (at 1 degree), 8.25Hz (at 3 degrees), and 9Hz (at 5 degrees), respectively. The frequency requirement was reduced for screening and carrying the iron ore material from the inlet zone to the outlet zone compared to coal material. For both coal and iron ore, the optimal frequency has resulted in the highest efficiency. It was also observed that the higher and lower frequency condition has resulted in higher retention of coal particles than iron ore particles; thereby, some of the undersized particles passing through screen slots and efficiency were reduced. It was observed that for all conditions of screening coal and iron ore, the drop in the efficiency was also due to the collection of the particles near the non-separation zone, i.e., near the sidewalls of the screen deck, which was more for higher frequency. This has led to reduced undersized particles passing through the screen slots, which reduces efficiency. It was also observed that the frequency requirement of the high-density iron ore material was less compared to the low-density coal material.

4.2 Effect of screening coal and iron ore at 6% moisture for varying angular position and frequency

Table 4.2. Screen efficiency of coal and iron ore with 6% moisture for different angular conditions.

Frequency of vibration in Hz	Screening efficiency of 6% moisture coal			Screening efficiency of 6% moisture iron ore		
	5^0	3^0	1^0	5^0	3^0	1^0
4.00	55.24	58.05	63.98	78.89	76.48	74.33
4.25	55.46	58.41	64.23	79.46	77.21	75.18
4.50	55.63	58.93	64.61	80.19	77.92	75.74
4.75	55.81	59.67	64.87	80.79	78.59	76.37
5.00	56.01	60.34	65.08	81.38	79.19	77.12
5.25	56.29	60.87	65.29	82.12	79.93	77.81
5.50	56.67	61.26	65.63	82.64	80.38	78.45
5.75	56.98	61.73	65.98	83.01	80.89	79.10
6.00	57.32	62.49	66.76	83.63	81.58	79.64
6.25	57.63	62.78	66.93	84.54	82.12	80.19
6.50	57.98	62.96	67.65	85.43	82.77	80.78
6.75	58.25	63.21	68.57	86.04	83.23	81.21
7.00	58.41	63.54	69.18	86.56	83.94	81.76
7.25	58.64	63.83	69.42	87.14	84.35	82.35
7.50	58.82	64.12	69.91	87.92	85.13	81.56
7.75	59.03	64.36	70.86	88.45	85.69	80.88
8.00	59.26	64.78	71.53	89.17	86.43	80.41
8.25	59.62	65.01	71.89	89.73	85.89	79.93
8.50	60.29	65.49	72.36	90.45	85.42	79.39
8.75	61.01	65.90	72.95	90.02	84.82	78.84
9.00	61.86	66.31	73.54	89.67	84.19	78.13
9.25	62.13	66.73	74.31	89.16	83.71	77.31
9.50	62.49	67.16	74.87	88.54	83.15	76.72
9.75	62.87	67.89	75.64	87.93	82.74	76.19
10.00	63.25	68.48	75.21	87.32	82.19	75.76
10.25	63.69	68.77	74.94	86.51	81.56	75.16
10.50	64.12	69.03	74.41	86.07	79.86	74.86
10.75	64.76	69.52	73.67	85.53	79.17	74.27
11.00	65.23	70.24	73.31	84.78	78.36	73.70
11.25	64.70	69.96	73.12	84.39	77.91	73.23

11.50	63.59	69.76	72.69	83.78	77.43	72.84
11.75	62.54	69.31	72.34	83.13	76.90	72.53
12.00	61.25	68.23	71.87	82.54	76.42	71.92

Table 4.2 shows the screen efficiency of coal and iron ore with 6% moisture for different angular conditions. Fig. 4.4 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 1 degree and 6% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 63.98%. The efficiency increases significantly (from 64.23% to 74.87%) with an increase in frequency (from 4.25Hz to 9.50Hz). The efficiency value stabilizes around 75.64% at a frequency of 9.75Hz and decreases to 71.87% at 12Hz. Fig. 4.4 also shows the results of screening iron ore; the efficiency obtained at a frequency of 4Hz was 74.33%. The efficiency increases significantly (from 75.18% to 81.76%) with an increase in frequency (from 4.25Hz to 7Hz). The efficiency value stabilizes around 82.35% at a frequency of 7.25Hz and decreases to 74.27% at 12Hz.

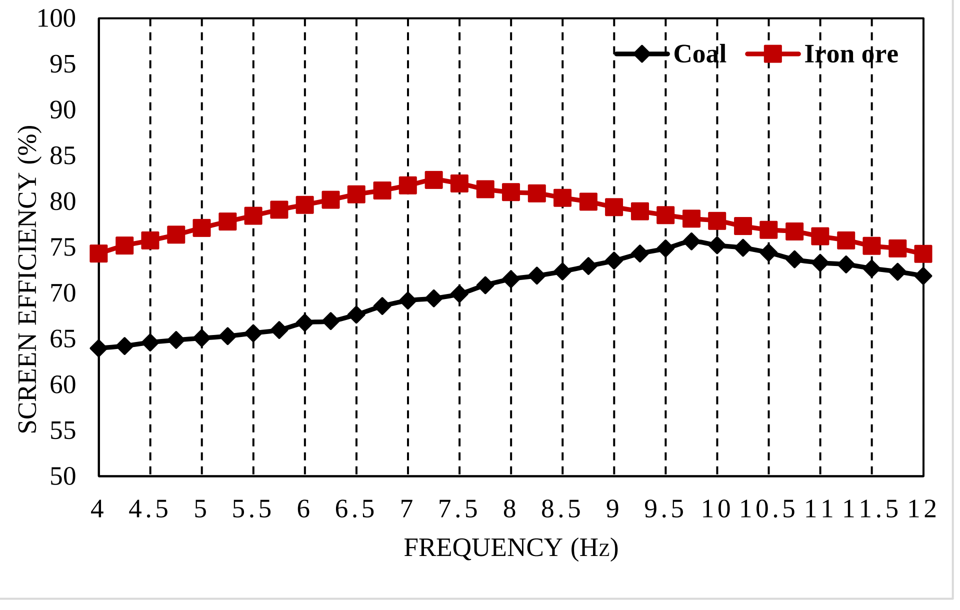


Fig. 4.4 Vibratory screen efficiency of coal and iron ore maintained at 6% moisture and 1^0

Plotting the efficiency test results against the screen's frequency for screening coal and iron ore at 1 degree shows that efficiency for screening 6% moisture material was good at a 1 degree upward slope. The upward slope screening has resulted in more residence time and high stratification. The higher stratification leads to faster particle movement through the screen slots.

Fig. 4.5 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 3 degrees and 4% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 58.05%. The efficiency increases significantly (from 58.41% to 69.52%) with an increase in frequency (from 4.25Hz to 10.75Hz). The efficiency value stabilizes around 70.24% at a frequency of 11Hz and decreases to 68.23% at 12Hz. Fig. 4.5 also shows the results for screening iron ore; the efficiency obtained at a frequency of 4Hz was 76.48%. The efficiency increases significantly (from 77.21% to 85.69%) with an increase in frequency (from 4.25Hz to 7.75Hz). The efficiency value stabilizes around 86.43% at a frequency of 8Hz and decreases to 76.42% at 12Hz.

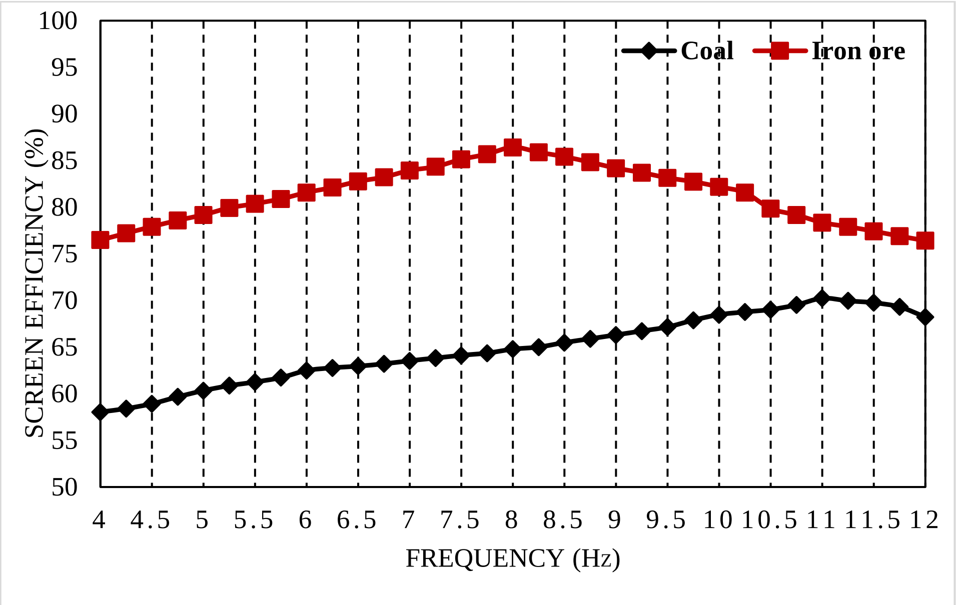


Fig. 4.5 Vibratory screen efficiency of coal and iron ore maintained at 6% moisture and 3^0

From Fig. 4.4 and Fig. 4.5, it was clear that the increase in the angular position has resulted in a decrease in the efficiency of coal and an increase in the efficiency of iron ore. Although screening of 6% moist coal at an angular position of 3 degrees has increased the residence time of the particles, some of the coal particle movement for the inlet to outlet zone of the screen was reduced. This has resulted in the accumulation of coal at the inlet zone of the screen deck, which has resulted in low efficiency. Screening iron ore with 6% moisture at 3 degrees has resulted in high residence time, high stratification, and more particle passage through the screen slots. So, the recovery of iron ore undersized particles and efficiency was higher compared to coal.

Fig. 4.6 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 5 degrees and 4% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 55.24%. The efficiency increases significantly (from 55.46% to 64.76%) with an increase in frequency (from 4.25Hz to 10.75Hz). The efficiency value stabilizes around 65.23% at a frequency of 11Hz and decreases to 61.25% at 12Hz. Fig. 4.6 also shows the results of screening iron ore; the efficiency obtained at a frequency of 4Hz was 78.89%. The efficiency increases significantly (from 79.46% to 89.73%) with an increase in frequency (from 4.25Hz to 8.25Hz). The efficiency value stabilizes around 90.45% at a frequency of 8.50Hz and decreases to 82.54% at 12Hz.

From Fig. 4.6, it was clear that the increase in angular position to 5 degrees for screening coal and iron ore has resulted in a similar pattern of reducing the efficiency of coal and increasing the efficiency of iron ore. The screening of coal at 5 degrees has increased the accumulation of more coal particles near the inlet zone, which has reduced the probability of undersized coal particles passing through screen slots. It was also observed that the irregularity of the particle shape had caused numerous attempts for the near-size particles to reorient and pass through the screen slots. Reorientation was reduced for coal particles at a higher angular position due to low frequency. Iron ore screening has resulted in good particle movement on the screen deck, increased residence time, and high iron ore undersized particles passing through the screen slots.

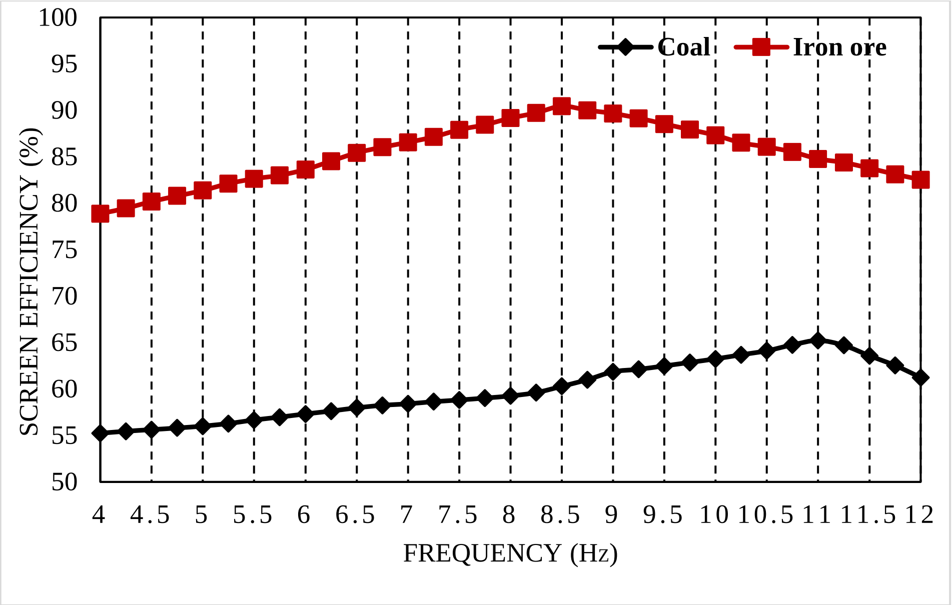


Fig. 4.6 Vibratory screen efficiency of coal and iron ore maintained at 6% moisture and 5^0

From Fig. 4.4, 4.5, and 4.6, it was clear that the efficiency of iron ore was highest as the angular position was increased from 1 to 5 degrees. But the efficiency of coal was reduced as the angular position was increased. It was observed that the difference in the behavior of screening coal and iron ore was majorly due to the density difference of the material. It was observed that the screening of iron ore had provided the faster movement of particles from the inlet zone to the outlet zone at low frequency compared to coal. For iron ore, the movement of particles has provided more opportunities for the particles to pass through the screen slots. For coal, the increase in the angular position of the screen from 1 to 5 degrees, the accumulation of coal particles at the inlet zone was more due to the reduced movement of coal. Also, it prevented some of the undersized coal particles from passing through the screen slots.

4.3 Effect of screening coal and iron ore at 8% moisture for varying angular position and frequency

Table 4.3 Screen efficiency of coal and iron ore with 8% moisture for different angular conditions.

Frequency of vibration in Hz	Screening efficiency of 8% moisture coal			Screening efficiency of 8% moisture iron ore		
	5^0	**3^0**	**1^0**	**5^0**	**3^0**	**1^0**
4.00	50.32	52.14	56.79	70.79	73.37	71.97
4.25	50.57	52.43	56.98	71.17	74.09	72.75
4.50	50.73	52.81	57.32	71.88	74.87	73.21
4.75	50.98	53.56	57.64	72.66	75.46	74.03
5.00	51.24	53.90	57.85	73.13	76.23	74.70
5.25	51.53	54.02	58.37	73.81	76.95	75.07
5.50	51.86	54.26	58.81	74.43	77.64	75.64
5.75	52.01	54.47	59.16	74.92	78.46	76.04
6.00	52.15	54.63	59.42	75.46	79.32	76.55
6.25	52.34	54.81	59.63	76.28	80.14	77.21
6.50	52.59	54.98	59.87	77.01	80.85	77.96
6.75	52.71	55.32	60.01	77.64	81.44	78.64
7.00	52.88	55.69	60.26	78.03	82.13	78.03
7.25	53.02	55.83	60.94	78.64	82.78	77.54
7.50	53.43	55.96	61.57	79.18	83.91	76.90
7.75	53.65	56.25	62.07	79.80	83.18	76.19
8.00	53.98	56.52	62.25	80.39	82.74	75.51
8.25	54.12	56.98	62.47	79.57	82.08	74.79
8.50	54.36	57.35	62.61	78.73	81.54	74.02
8.75	54.53	58.13	62.88	78.12	80.95	73.72
9.00	54.69	58.64	63.11	77.65	80.26	73.04
9.25	54.83	58.79	63.46	77.04	78.67	72.54
9.50	54.99	58.93	62.86	76.59	78.03	71.62
9.75	55.17	59.07	61.66	75.97	77.56	70.89
10.00	55.48	59.21	60.94	75.19	76.90	69.97
10.25	55.71	59.74	60.71	74.46	76.11	69.12
10.50	56.02	59.14	60.44	73.93	75.45	68.64
10.75	56.45	58.49	59.96	73.24	74.91	68.02
11.00	56.63	57.36	59.32	72.59	74.19	67.66
11.25	56.97	57.01	59.13	71.98	73.48	67.02
11.50	56.12	56.73	58.87	71.02	72.69	66.74
11.75	55.50	56.46	58.45	70.45	72.13	66.15
12.00	54.76	55.90	58.04	69.27	71.44	65.37

Table 4.3 shows the screen efficiency of coal and iron ore with 8% moisture for different angular conditions. Fig. 4.7 shows the effect of frequencies on the efficiency

of screening coal and iron ore in the vibratory screen maintained at 1 degree and 8% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 56.79%. The efficiency increases significantly (from 56.98% to 63.11%) with an increase in frequency (from 4.25Hz to 9Hz). The efficiency value stabilizes around 63.46% at a frequency of 9.25Hz and decreases to 58.04% at 12Hz. Fig. 4.7 also shows the results of screening iron ore; the efficiency obtained at a frequency 4Hz was 71.97%. The efficiency increases significantly (from 72.75% to 77.96%) with an increase in frequency (from 4.25Hz to 6.50Hz). The efficiency value stabilizes around 78.64% at a frequency of 6.75Hz and decreases to 65.37% at 12Hz.

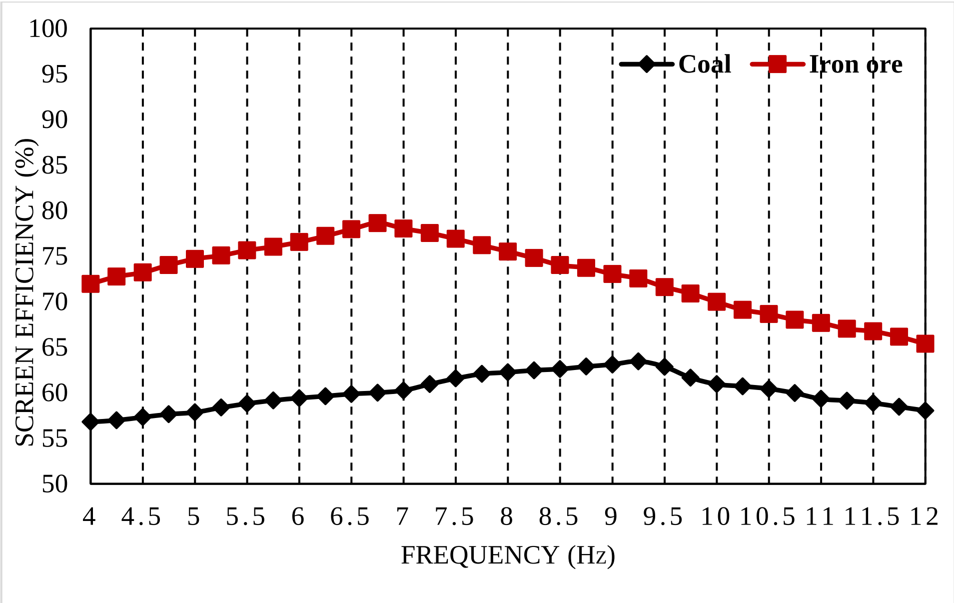


Fig. 4.7 Vibratory screen efficiency of coal and iron ore maintained at 8% moisture and 1^0

From Fig. 4.1, 4.4, and 4.7, it was clear that the increase in the moisture content has reduced the efficiency of coal and iron ore. It was observed that the drop in the efficiency of coal was more when compared to the efficiency of iron ore. As the moisture was increased, it was observed that the agglomeration of irregularly shaped coal particles was more and resulted in the high bonding between the fine particles and near-size particles (Liyanaarachchi et al. 2014; Özer, Basha, and Morsi 2017). The bonding has resulted in the filling of screen slots leading to high screen clogging for screening coal, and also, some of the coal particles were not moving towards the outlet zone (Cleary et al. 2018; Menezes et al. 2020). Higher screen clogging of the screen slots has reduced the percentage of screen slots opening area, thereby reducing the efficiency of coal.

Fig. 4.8 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 3 degrees and 8% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 52.14%. The efficiency increases significantly (from 52.43% to 59.21%) with an increase in frequency (from 4.25Hz to 10Hz). The efficiency value stabilizes around 59.74% at a frequency of 10.25Hz and decreases to 55.90% at 12Hz. Fig. 4.8 also shows the results of screening iron ore; the efficiency obtained at a frequency of 4Hz was 73.37%. The efficiency increases significantly (from 74.09% to 82.78%) with an increase in frequency (from 4.25Hz to 7.25Hz). The efficiency value stabilizes around 83.91% at a frequency of 7.50Hz and decreases to 71.44% at 12Hz.

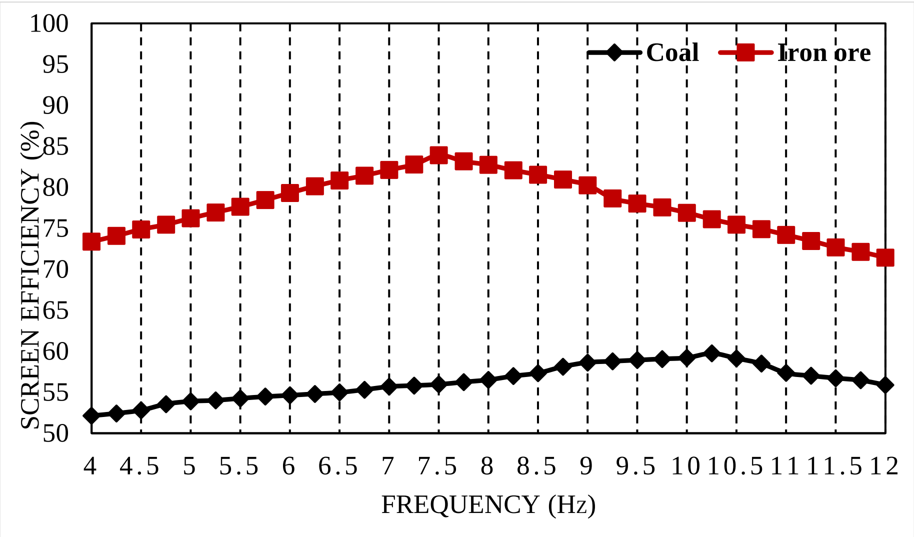


Fig. 4.8 Vibratory screen efficiency of coal and iron ore maintained at 8% moisture and 3^0

As the angular position of the screen was increased to 3 degrees, it was observed that the movement of coal particles from the inlet zone to the outlet zone was less. The reduction in particle movement has increased, resulting in more accumulation of coal particles and high screen clogging near the inlet zone resulting in low efficiency. For screening iron ore, it was observed that there was a small number of iron ore particles gathered near the inlet zone, and the agglomeration of the iron ore particles was lesser. Due to this, screen clogging was less, and the efficiency of iron ore was higher.

Fig. 4.9 shows the effect of frequencies on the efficiency of screening coal and iron ore in the vibratory screen maintained at 5 degrees and 8% moisture. For screening coal, the efficiency obtained at a frequency of 4Hz was 50.32%. The efficiency increases significantly (from 50.57% to 56.63%) with an increase in frequency (from 4.25Hz to 11Hz). The efficiency value stabilizes around 56.97% at a frequency of 11.25Hz and decreases to 54.76% at 12Hz. Fig. 4.9 also shows the results of screening iron ore; the efficiency obtained at a frequency of 4Hz was 70.79%. The efficiency increases significantly (from 71.17% to 79.80%) with an increase in frequency (from 4.25Hz to 7.75Hz). The efficiency value stabilizes around 80.39% at a frequency of 8Hz and decreases to 69.27% at 12Hz.

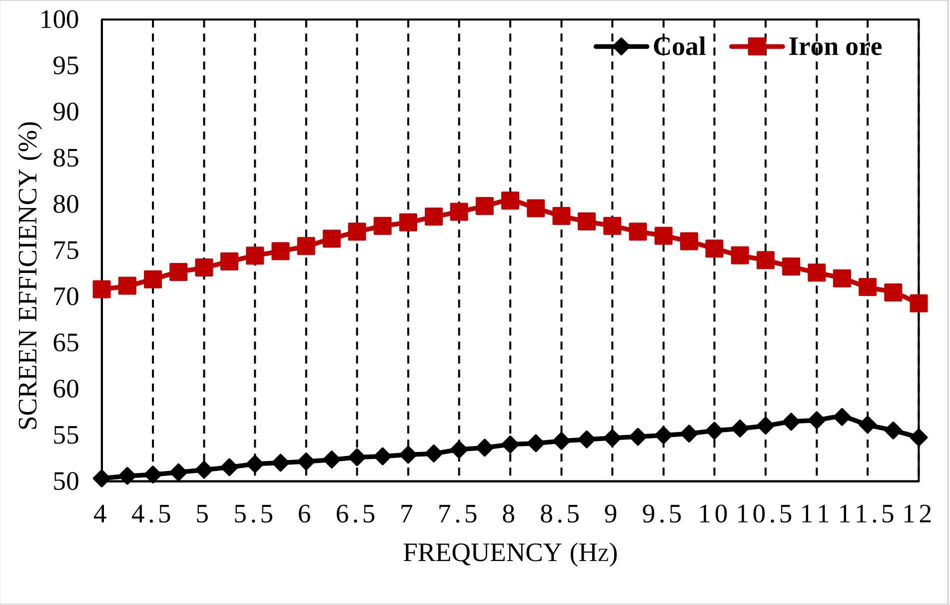


Fig. 4.9 Vibratory screen efficiency of coal and iron ore maintained at 8% moisture and 5^0

From Fig. 4.9, it was clear that a higher drop in efficiency of coal at 5 degrees was due to the high accumulation of coal particles near the inlet zone and screen clogging, which can be seen from Fig. 4.10. It was observed that as the moisture content of coal was increased, the particle stratification, passing of particles into the screen slot, and efficiency was reduced.

It was also observed that the screening of iron ore at 5 degrees had reduced the efficiency compared to screening at 3 degrees. This was majorly due to the reduced movement of some iron ore particles on the screen deck and the reduced accumulation of iron ore particles on the screen deck. It was also observed that the screen clogging was less for screening iron ore, which can be seen in Fig. 4.11. So, the efficiency was more for iron ore compared to coal.

Fig. 4.10 Clogging of coal

Fig. 4.11 Clogging of iron ore

The increase in the efficiency of iron ore was also due to the high density of iron ore. It was found that the higher density of iron ore also refers to the handling of a small amount of material compared to the low-density coal. As the material handling for iron ore was less, the number of near-sized particles, fine particles, and coarse particles was less. During sample preparation, the amount of water utilised to change the moisture content of coal was more compared to iron ore. This was due to the low density of coal, which leads to a large amount of material with more surface absorbing the moisture content. This has resulted in the requirement of a high amount of water for increasing coal moisture. So, the stratification was faster for iron ore particles compared to coal. It was also observed that the iron ore particles had a good particle movement for 3 and 5 degrees screening on an upward slope. Due to this movement of particles, all the iron ore particles on the screen deck were provided with more opportunities to pass through the screen slots than coal.

Although there was a drop in efficiency for screening coal at 3 and 5 degrees for all moisture conditions, screening in a 1 degree upward slope resulted in higher efficiency.

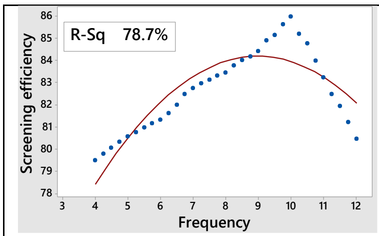
It was observed that the screen's optimum bed depth and rotational motion have resulted in high efficiency. The optimal bed depth has assisted in good particle segregation and particle movement on the screen deck (Harzanagh et al. 2018).

The horizontal motion of the rotational force caused the material to move from the inlet zone to the outlet zone of the screen deck. The horizontal motion also moves the oversized particles providing easy passing of the undersized particles through screen slots. The vertical motion of the rotational force caused particle agitation, particle mixing, and clear the screen slots providing an anti-clogging behavior. With the intermediate horizontal and vertical motion of the rotational force, the vibratory screen had a high residence time of the material on the screen deck, which caused the high passage of particles through the screen slots. From the results, it was clear that iron ore material can be screened with less screen clogging compared to coal. This shows that the anticlogging behavior of the high-density material such as iron ore was more for the developed vibratory screen.

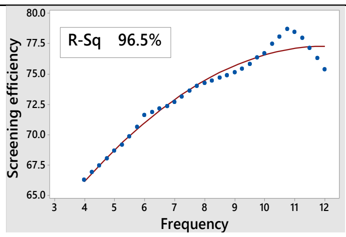
4.4 Prediction of efficiency using the regression model

After the experimentation, the predictive regression model was developed for efficiency with respect to the frequency variation for each moisture and angular condition. For each predictive model, P-value and R-squared values were obtained. P-value is a significant value that has to be less than 0.005. For all the conditions of screening coal and iron ore, the P-value was 0. This shows that the quality of the model was good. R-squared value shows the closeness in the correlation of the experiment results and prediction results in percentage.

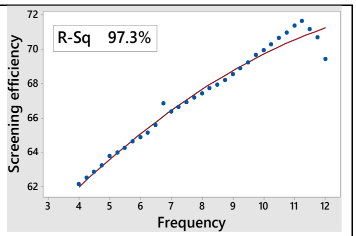
Fig. 4.12a-i shows the regression data fitting results of efficiency for all experimental conditions of screening coal. For 4% moisture content, the R-squared value for 1 degree, 3 degrees and 5 degrees was 78.7%, 96.5%, and 97.3%, respectively. The R-squared value of 3 degrees and 5 degrees was found to be more accurate compared to 1 degree. 78.7% R-squared value for predicting screening results at 1 degree was in an acceptable range. For 6% moisture content, the R-squared value for 1 degree, 3 degrees, and 5 degrees was 91.7%, 97.9%, and 97.1%, respectively. For 8% moisture content, the R-squared value for 1 degree, 3 degrees, and 5 degrees was 87.3%, 85.6%, and 95.3%, respectively. All the predictive values of screening coal with 6% and 8% moisture, the R squared value, were found to be highly accurate for the developed regression model.



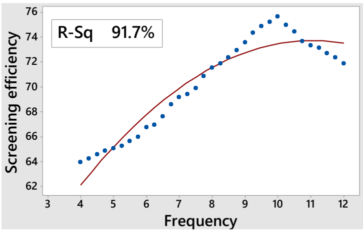
a. 4% moisture, 1 degree



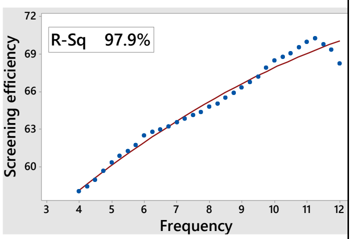
b. 4% moisture, 3 degrees



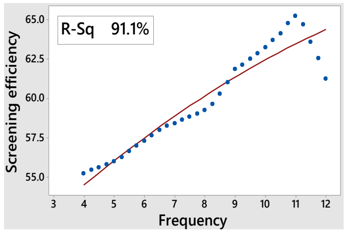
c. 4% moisture, 5 degrees



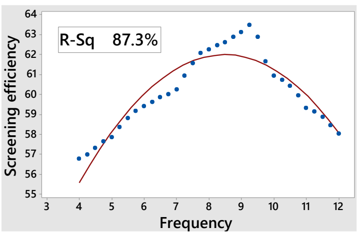
d. 6% moisture, 1 degree



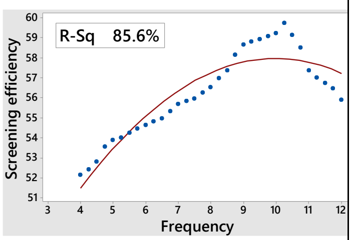
e. 6% moisture, 3 degrees



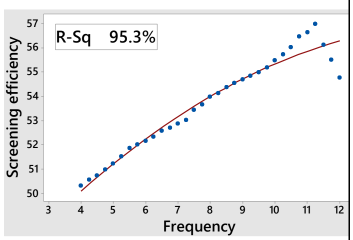
f. 6% moisture, 5 degrees



g. 8% moisture, 1 degree



h. 8% moisture, 3 degrees



i. 8% moisture, 5 degrees

Fig. 4.12 Regression data fitting results for all the conditions of screening coal

Fig. 4.13a-i shows the regression data fitting results of efficiency for all experimental conditions of screening iron ore. For 4% moisture content, the R-squared value for 1 degree, 3 degrees and 5 degrees was 93.4%, 89.8%, and 88.5%, respectively. For 6% moisture content, the R-squared value for 1 degree, 3 degrees, and 5 degrees was 89.8%, 94.2%, and 93.3%, respectively. For 8% moisture content, the R-squared value for 1 degree, 3 degrees and 5 degrees was 92.5%, 92.4%, and 94.9%, respectively. Fig. 4.12a-i and Fig. 4.13a-i observed that the regression prediction results of iron ore had provided more accurate results than the prediction results of coal.

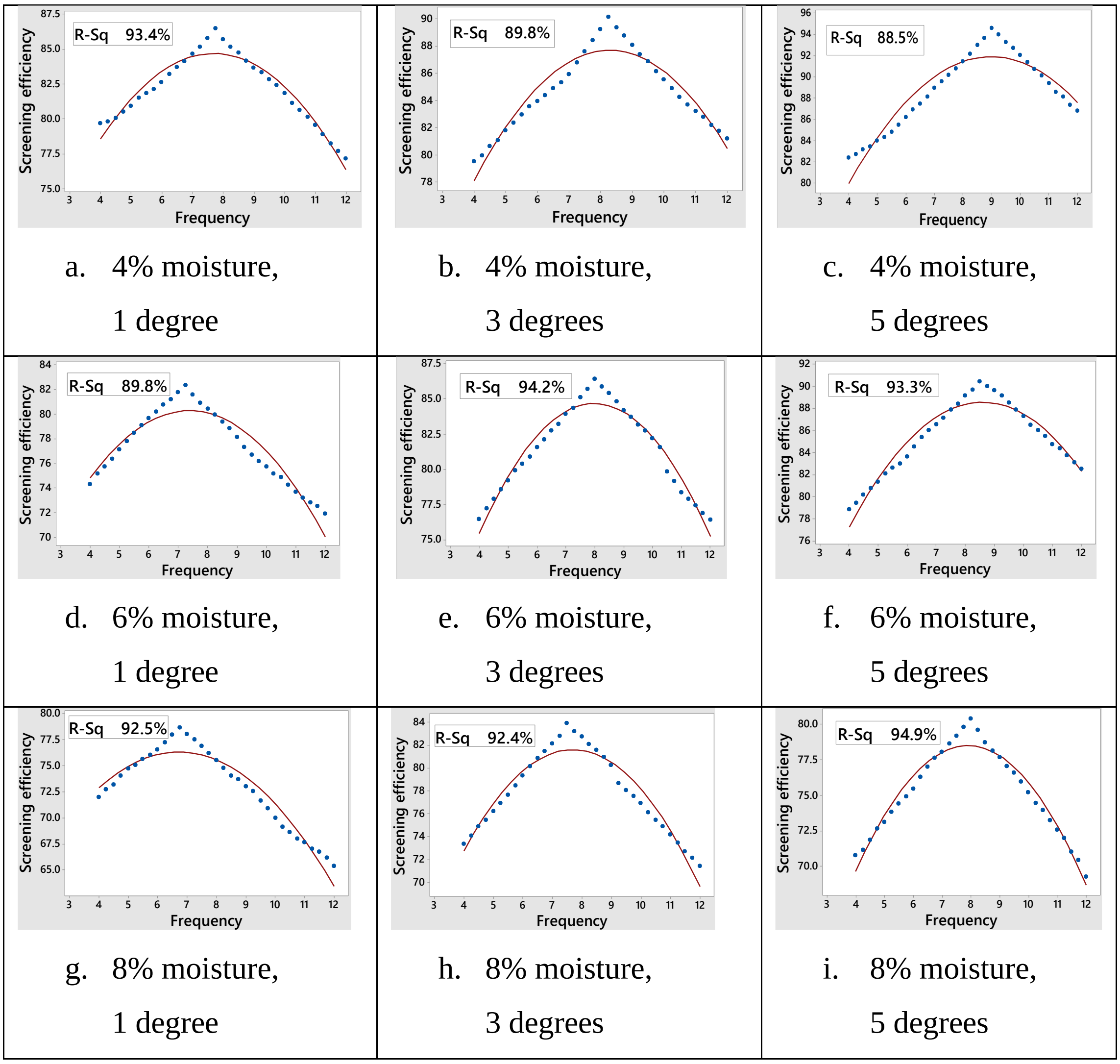


Fig. 4.13 Regression data fitting results for all the conditions of screening iron ore

4.5 Prediction of efficiency using the Artificial neural network model

Fig. 4.14a-i and Fig. 4.15a-i show the artificial neural network data fitting results for all the conditions of screening coal and iron ore, respectively. The predictive model was developed using an artificial neural network for efficiency with respect to the frequency variation for each moisture and angular condition. For each predictive model, R-value validation, R-value overall, and R-squared value were obtained. R-value overall shows the closeness in the correlation between the experimental results and prediction results. From Fig. 4.14a-i and Fig. 4.15a-i, it was clear that the prediction data fit well with experimental data.

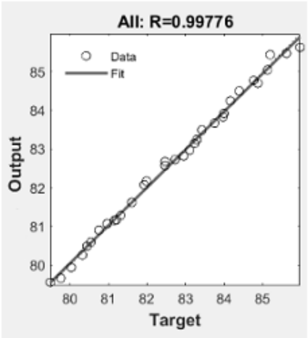
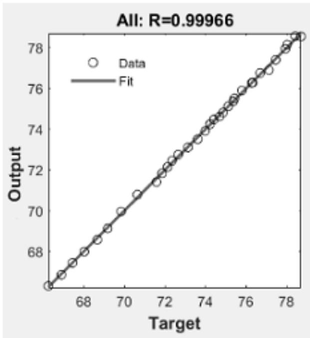
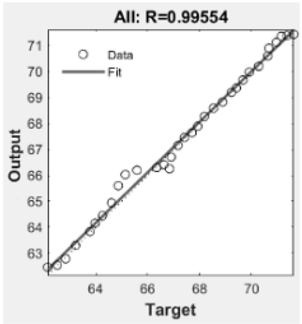
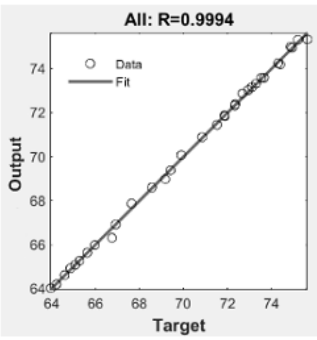
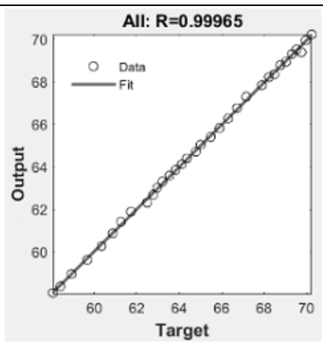
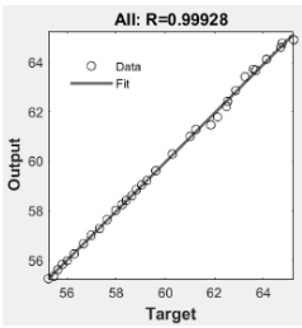
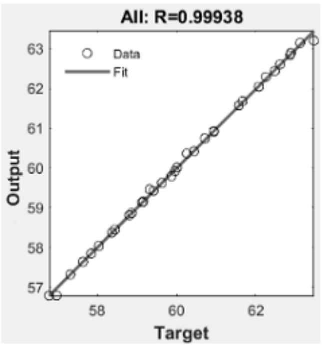
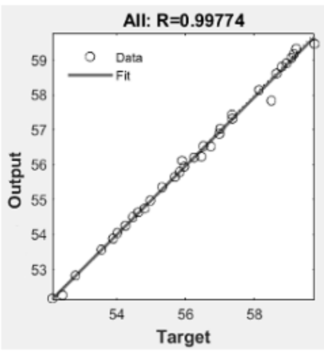
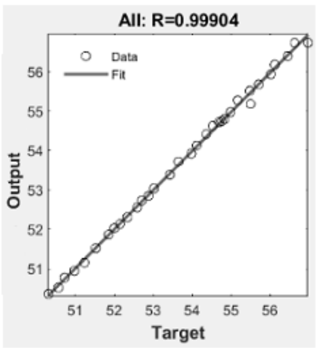
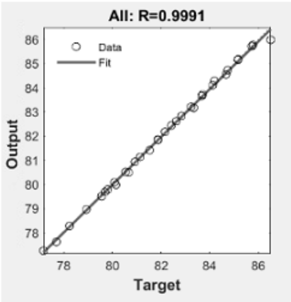
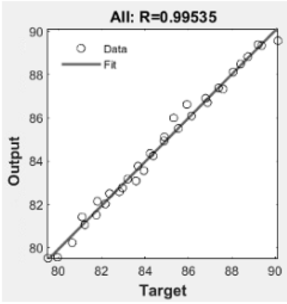
 a. 4% moisture, 1 degree	 b. 4% moisture, 3 degrees	 c. 4% moisture, 5 degrees
 d. 6% moisture, 1 degree	 e. 6% moisture, 3 degrees	 f. 6% moisture, 5 degrees
 g. 8% moisture, 1 degree	 h. 8% moisture, 3 degrees	 i. 8% moisture, 5 degrees

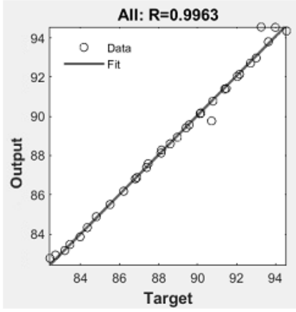
Fig. 4.14 ANN overall data fitting results for all the conditions of screening coal



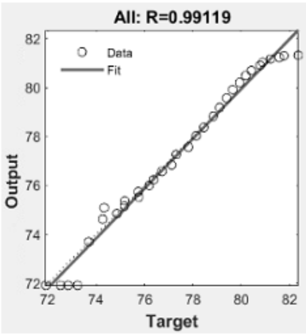
a. 4% moisture, 1 degree



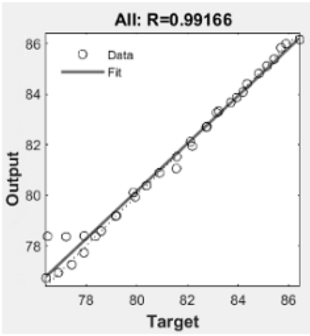
b. 4% moisture, 3 degrees



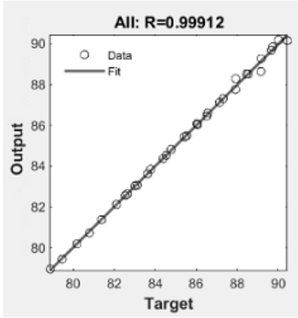
c. 4% moisture, 5 degrees



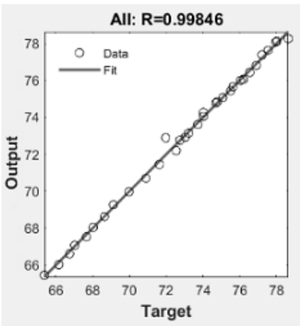
d. 6% moisture, 1 degree



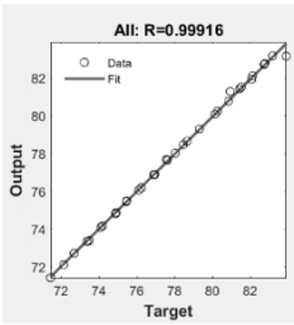
e. 6% moisture, 3 degrees



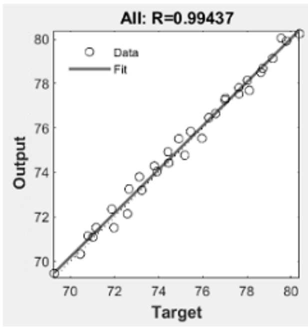
f. 6% moisture, 5 degrees



g. 8% moisture, 1 degree



h. 8% moisture, 3 degrees



i. 8% moisture, 5 degrees

Fig. 4.15 ANN overall data fitting results for all the conditions of screening iron ore

Table 4.4 and Table 4.5 show ANN prediction results of efficiency for all experimental conditions of screening coal and iron ore, respectively. Table 4.4 and Table 4.5 showed that the R squared value obtained was more than 99% for all the screening conditions. This shows that the modeling with an artificial neural network results in developing a highly accurate model for screening coal and iron ore. The closeness in R-value validation with the R-value overall provides the validation of the predictive model. From Table 4.4 and Table 4.5, it was clear that the developed model was valid and accurate.

Table 4.4 ANN prediction results of efficiency for all experimental conditions of screening coal.

Moisture content	**Screen angular position (^{0})**	**Training R**	**Test R**	**Validation R**	**All R**	**Regression coefficient R-squared**
4%	1	0.9977	0.9979	0.9982	0.9977	99.55%
	3	0.9997	0.9998	0.9994	0.9996	99.93%
	5	0.9948	0.9961	0.9994	0.9955	99.10%
6%	1	0.9991	0.9999	0.9997	0.9994	99.88%
	3	0.9995	0.9999	0.9997	0.9996	99.93%
	5	0.9990	0.9999	0.9996	0.9992	99.85%
8%	1	0.9993	0.9979	0.9999	0.9993	99.87%
	3	0.9969	0.9999	0.9999	0.9977	99.55%
	5	0.9991	0.9973	0.9996	0.9990	99.81%

Table 4.5 ANN prediction results of efficiency for all experimental conditions of screening iron ore

Moisture content	Screen angular position (^{0})	Training R	Test R	Validation R	All R	Regression coefficient R-squared
4%	1	0.9986	0.9999	0.9999	0.9991	99.82%
	3	0.99489	0.9977	0.9973	0.9953	99.07%
	5	0.9969	0.9954	0.9997	0.9963	99.26%
6%	1	0.9949	0.9917	0.9956	0.9911	98.24%
	3	0.9894	0.9996	0.9975	0.9916	98.33%
	5	0.9988	0.9999	0.9994	0.9991	99.82%
8%	1	0.9978	0.9996	0.9998	0.9984	99.69%
	3	0.9992	0.9999	0.9996	0.9991	99.83%
	5	0.9942	0.9919	0.9998	0.9943	98.87%

4.6 Validation of regression and ANN model using probability plot of residuals

Fig. 4.16 and 4.18 show the probability plot of residual of regression models for all the experimental conditions of coal and iron ore. Fig. 4.17 and 4.19 show the histogram of residual of regression models for all the experimental conditions of coal and iron ore. From Fig. 4.16 to 4.19, it was clear that the residuals are within the normal line and also are independent of one another. Fig. 4.16 to 4.19 also show that the standard deviation value indicates the overall spread of errors ranging from 0.4 to 1.3. The standard deviation value was low but in the acceptable range. The normality, independent, and standard deviation results of the probability plot show that the developed regression model for all the experimental conditions of coal and iron ore fits well with the data.

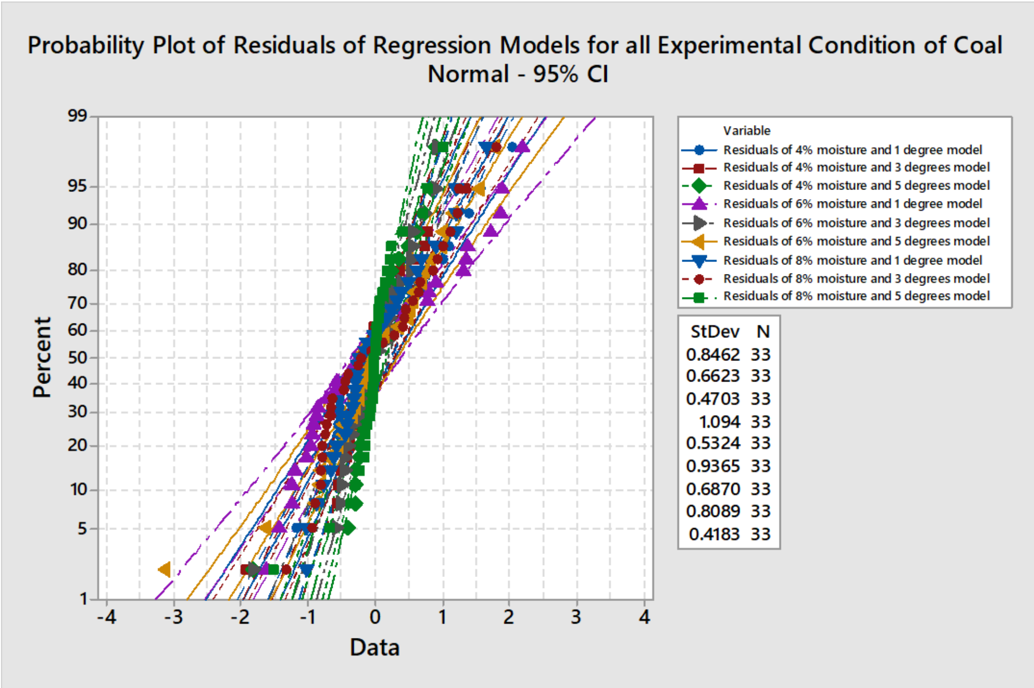


Fig. 4.16 Probability plot of residual of regression models for all the experimental conditions of coal

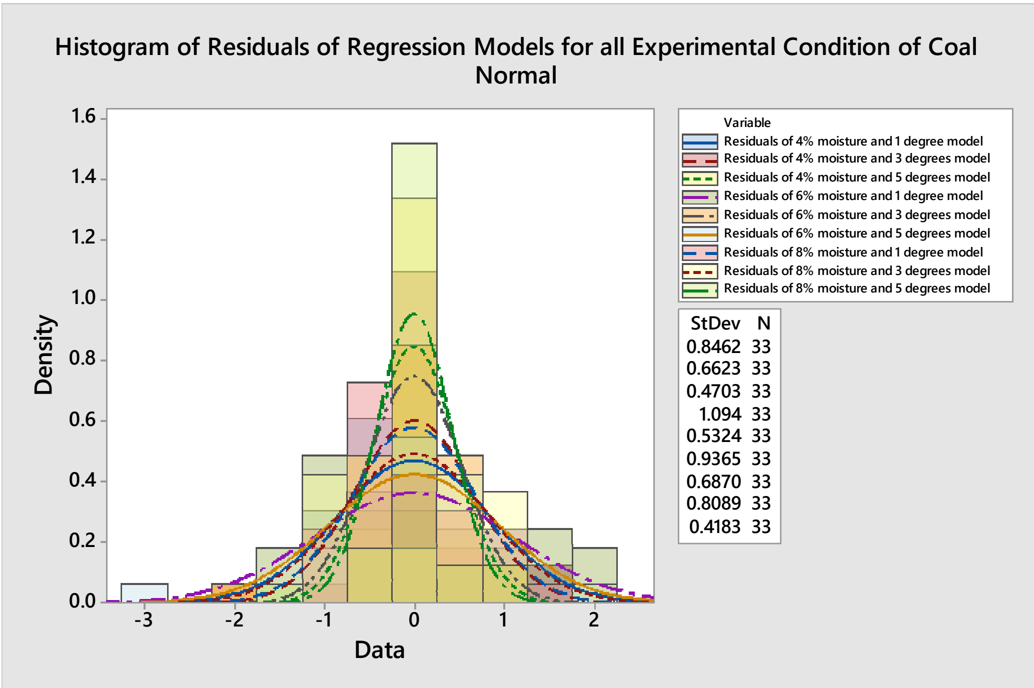


Fig. 4.17 Histogram of residual of regression models for all the experimental conditions of coal

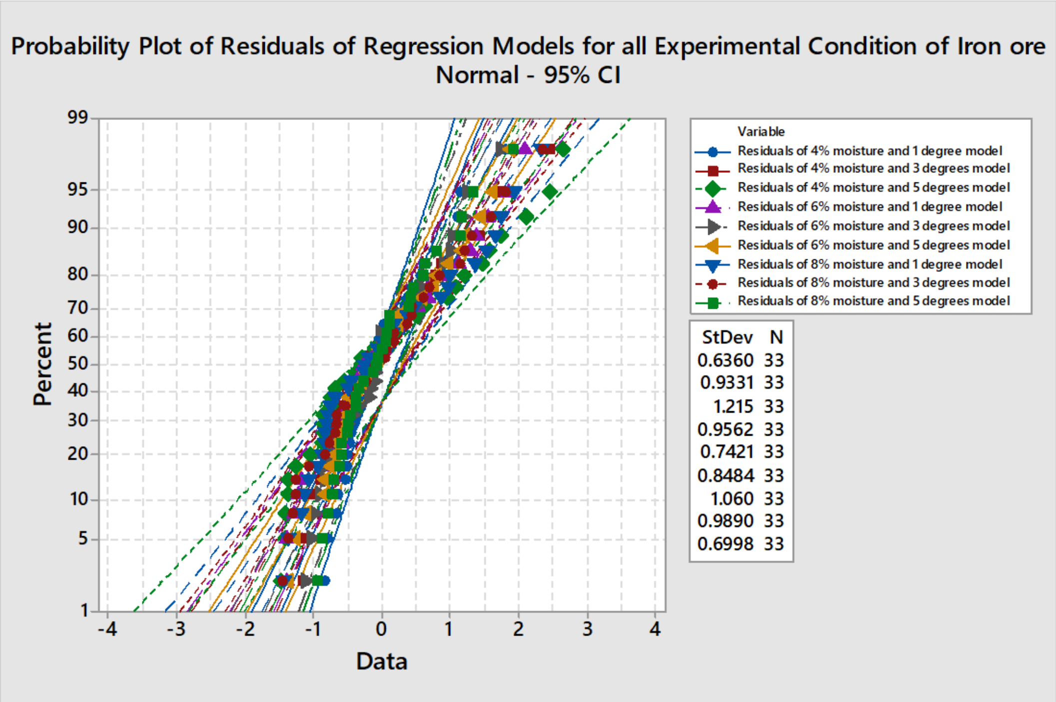


Fig. 4.18 Probability plot of residual of regression models for all the experimental conditions of iron ore

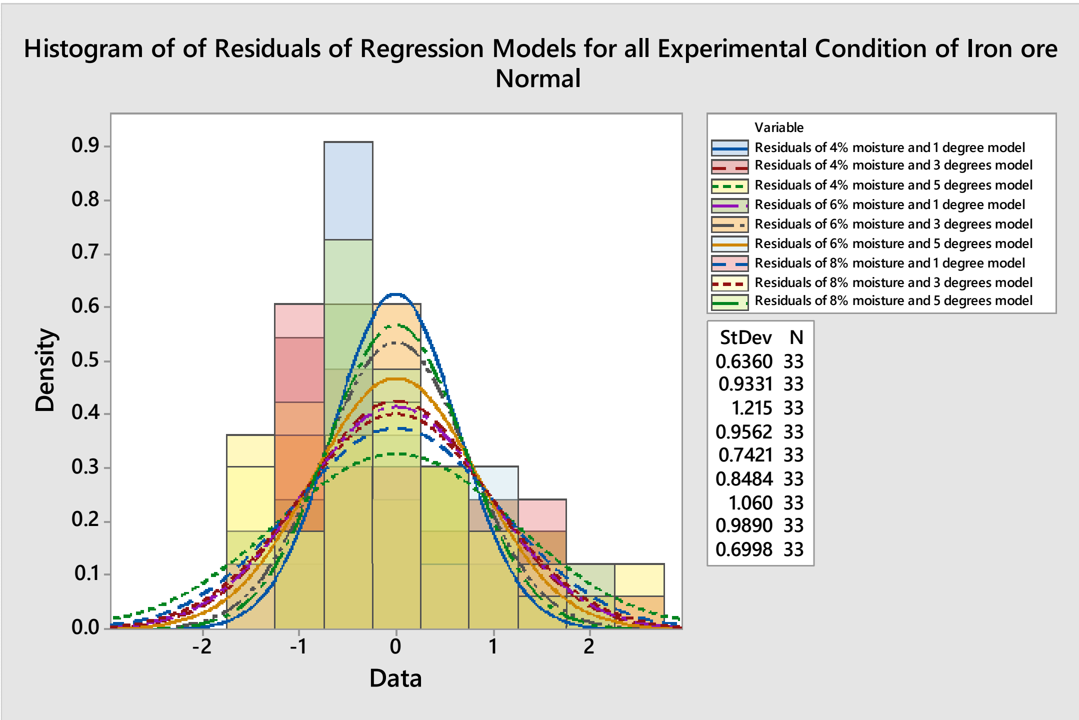


Fig. 4.19 Histogram of residual of regression models for all the experimental conditions of iron ore

Fig. 4.20 and 4.22 show the probability plot of residual of ANN models for all the experimental conditions of coal and iron ore, respectively. Fig. 4.21 and 4.23 show the probability plot of residual of ANN models for all the experimental conditions of coal and iron ore, respectively. From Fig. 4.20 to 4.23, it was clear that the residuals are within the normal line and also are independent of one another. Fig. 4.20 to 4.23 also show that the standard deviation value was in the range of 0.1, which was significantly less for the ANN model than the regression model. Fig. 4.20 and 4.22 show the vertical spread of the data around the normal line appears to be fairly constant, which satisfies the condition of homoscedasticity (Mohanraj et al. 2021). The normality, independent, low standard deviation, and homoscedasticity results of the probability plot show that the developed ANN model provides better prediction results than the regression model for all the experimental conditions of coal and iron ore.

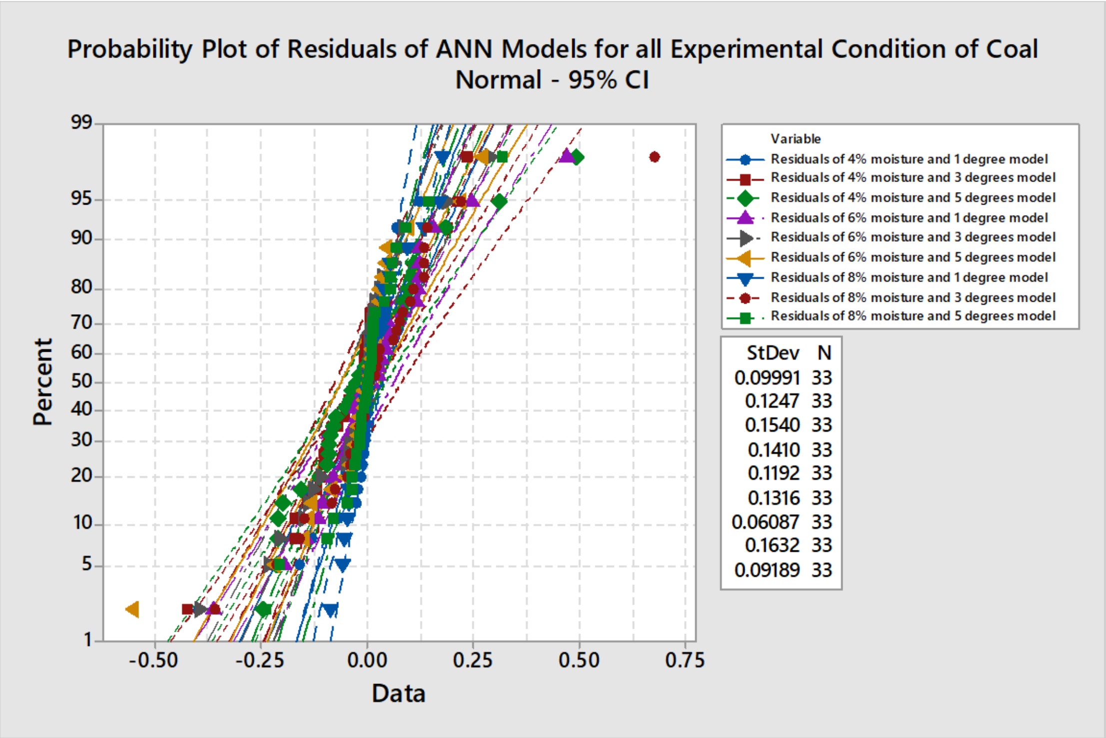


Fig. 4.20 Probability plot of residual of ANN models for all the experimental conditions of coal

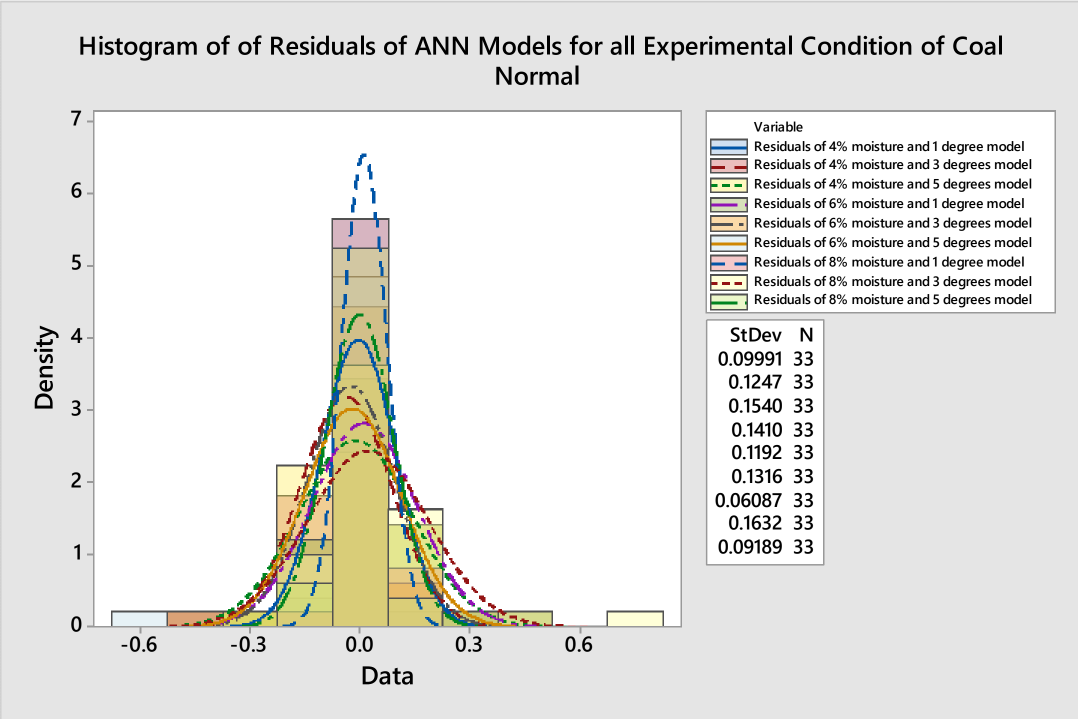


Fig. 4.21 Histogram of residual of ANN models for all the experimental conditions of coal

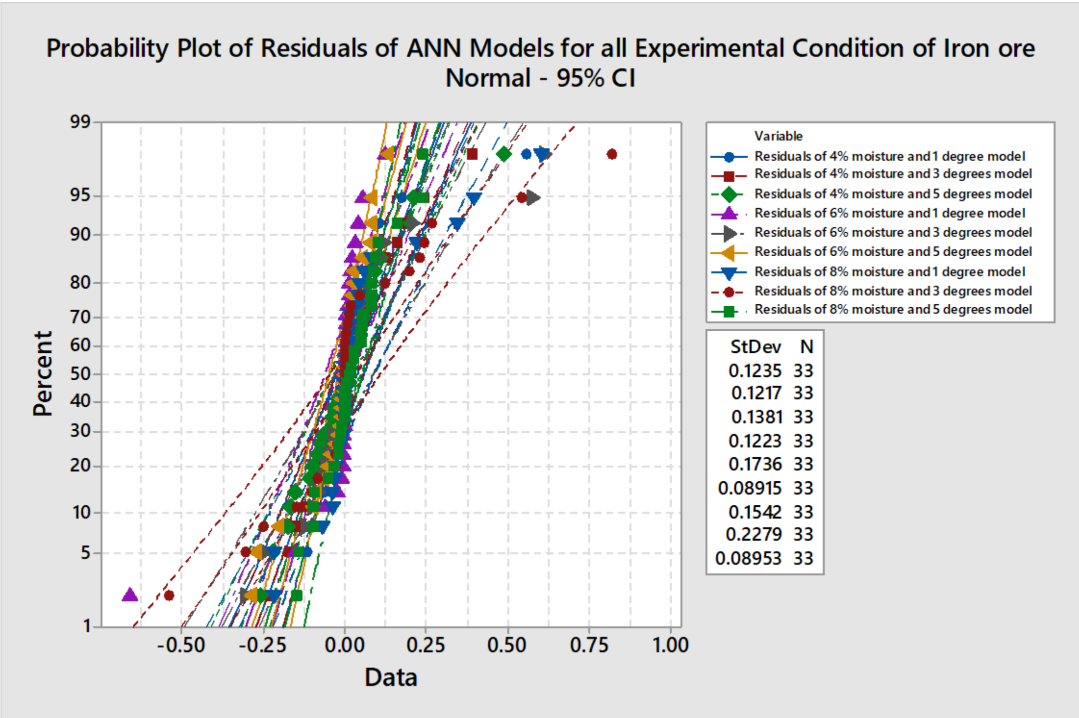


Fig. 4.22 Probability plot of residual of ANN models for all the experimental conditions of iron ore

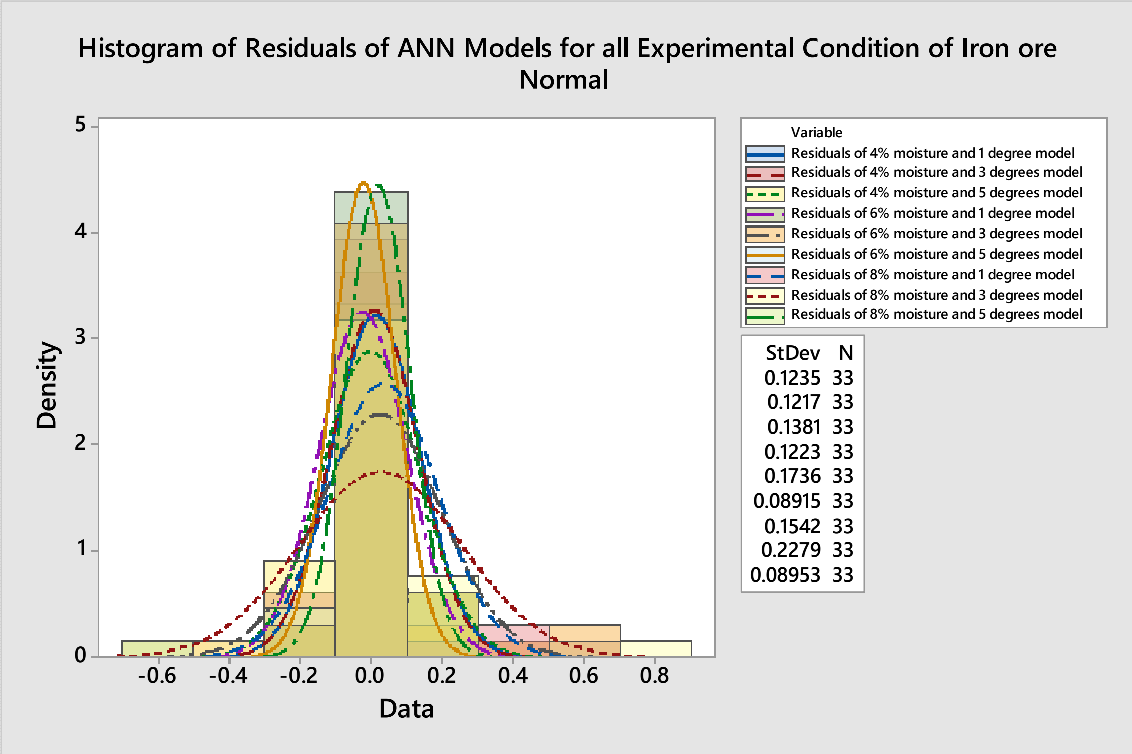


Fig. 4.23 Histogram of residual of ANN models for all the experimental conditions of iron ore

From the regression and artificial neural network prediction results, it was clear that the artificial neural network model's R-squared value was higher than the R-squared value of the regression model. From the regression and artificial neural network residual analysis results, it was clear that the data fitting of the artificial neural network model was higher than the regression model. This shows that the artificial neural network predictive model has provided better results than the predictive regression model. It was found that the artificial neural network predictive model provides better relations for the complex problem of screening coal and iron ore.

4.7 Statistical optimisation of efficiency using Taguchi L27 Design of Experiments

Table 4.6 shows the experimental design generated using the Taguchi L27 technique for the optimisation of screening machine performance. The Taguchi L27 design technique was used to optimize the screening machine's operational parameters in the present work. Therefore, it is necessary to validate the results of the Taguchi technique. The regression coefficient separating coal and iron ore was 99.6% and 99.8%, respectively, which shows the closeness and accuracy between the predicted and experimental values. So, the developed model can be applied for the optimisation of the operating parameters of the vibrating screen.

Table 4.6 Taguchi L27 Design of Experiments (DOE) results

Moisture content (%)	**Angle (degree)**	**Frequency (Hz)**	**Efficiency of coal (%)**	**Efficiency of iron ore (%)**
4	1	6	81.32	82.62
4	1	9	84.39	86.81
4	1	12	80.45	82.84
4	3	6	71.58	83.94
4	3	9	75.12	89.13
4	3	12	75.36	83.20
4	5	6	64.87	86.21
4	5	9	68.54	94.56
4	5	12	69.42	86.81
6	1	6	66.76	79.64
6	1	9	73.54	79.39
6	1	12	71.87	74.27
6	3	6	62.49	81.58
6	3	9	66.31	84.19
6	3	12	68.23	76.42
6	5	6	57.32	83.63
6	5	9	61.86	89.67
6	5	12	61.25	82.54
8	1	6	59.42	76.55
8	1	9	63.11	73.04
8	1	12	58.04	65.37
8	3	6	54.63	79.32
8	3	9	58.64	80.26
8	3	12	55.90	71.44
8	5	6	52.15	75.46
8	5	9	54.69	77.65
8	5	12	54.76	69.27

4.7.1. Effects of moisture content on screening performance

Fig. 4.24 and 4.25 show the effect of moisture content on coal and iron ore screening performance in the vibrating screen. The signal-to-noise ratio (S/N ratio) selected was larger the better, which indicates that the lower moisture content was yielding higher efficiency for screening coal and iron ore. In low moisture screening conditions, the fine and coarse particles had lesser adhesion, causing more particles to pass through the screen. Therefore, the screening efficiency was higher for coal and iron ore screening at lower moisture conditions. In medium moisture conditions, some fine particles were adhering to the coarse particles during the particle mixing on the screen.

The particle adhesion on the screen was reducing the particle passage through the screen. Therefore, there is a slight drop in the efficiency of screening at medium moisture conditions. More fine particles were subjected to adhesion with coarse particles in high moisture conditions, as shown in Fig. 19a and 19b. Particle adhesion has caused an increase in the particles' size, which led to the reduced particle passing through the screen. At high moisture conditions, it was also seen that the adhesion between the fine particles had caused the increase in the near-size particles. This particle produces high screen hole filling, which blocks other fine particles' paths from passing through the screen. Therefore, the efficiency of coal and iron ore screening was reduced for high moisture conditions.

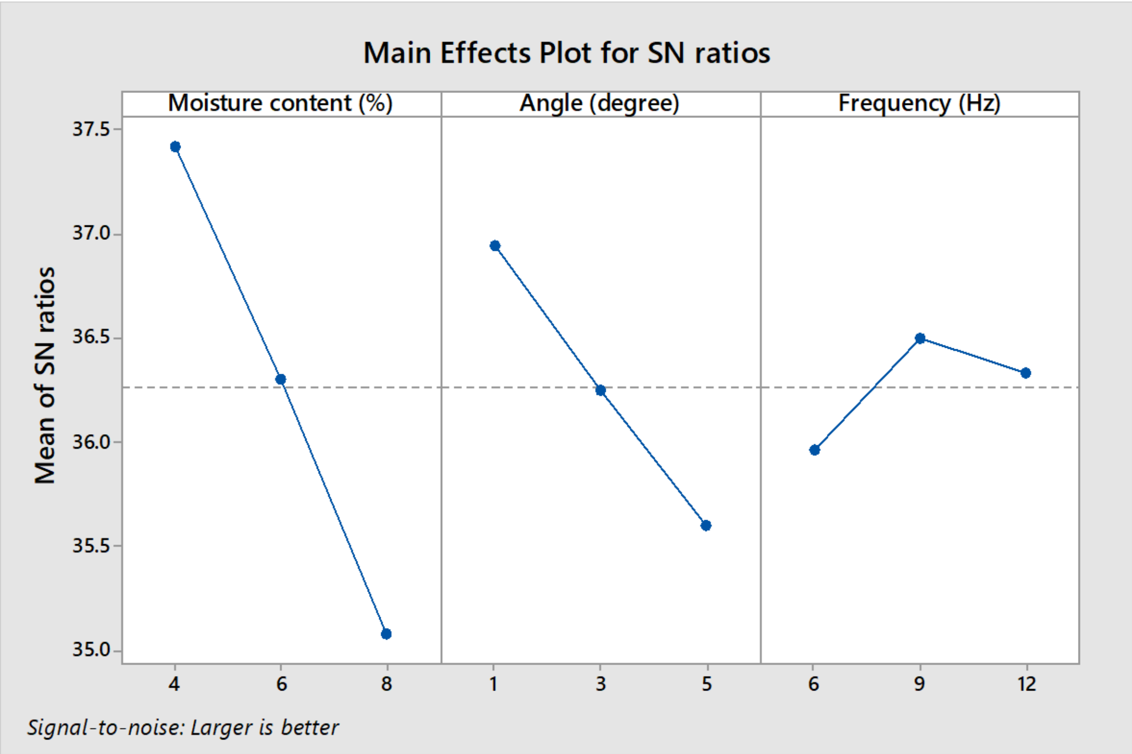


Fig. 4.24 Main effect plot obtained for moisture content, angle, and frequency on coal screening performance

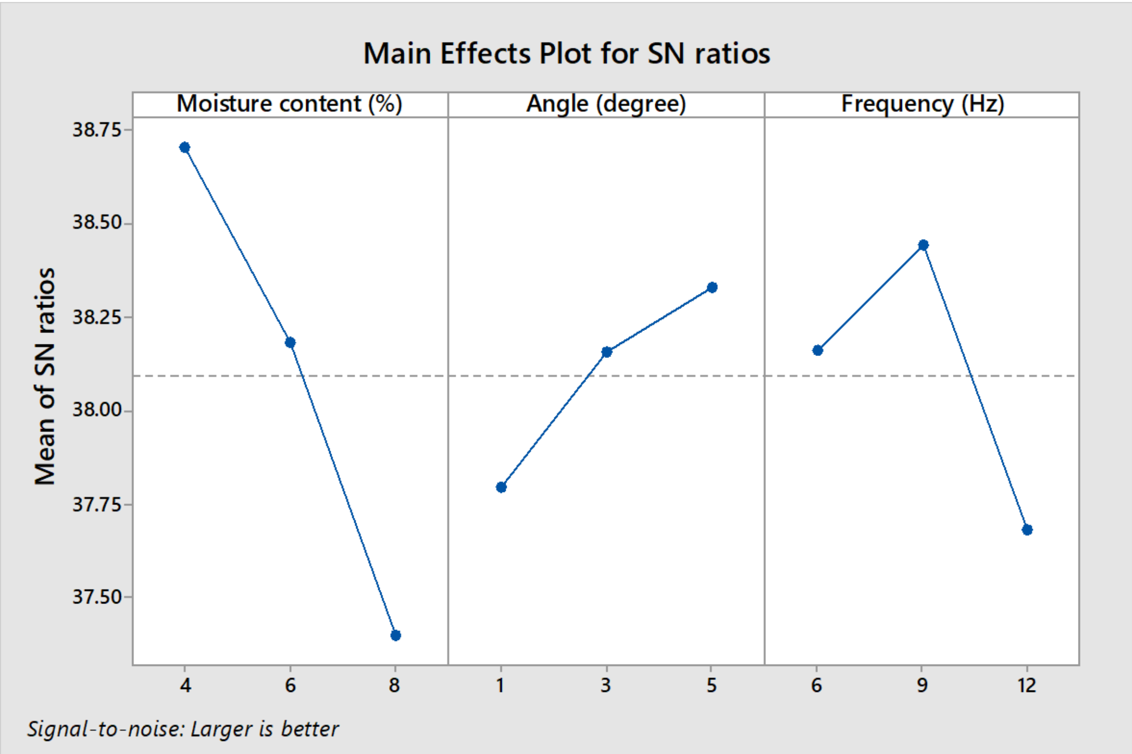


Fig. 4.25 Main effect plot obtained for moisture content, angle, and frequency on iron ore screening performance

4.7.2. Effects of angle on screening performance

Fig. 4.24 and 4.25 show the effect of angle on coal and iron ore screening performance in the vibrating screen. The signal-to-noise ratio (S/N ratio) selected was larger the better, which indicates that the lower angle at an upward slope was yielding higher efficiency for screening coal. At lower angle conditions for screening coal, the particle movement and particle mixing on the screen were higher. The particle time on the screen has caused enough time for the fine particles to pass through the screen was higher. It was also found that more fine particles had passed through the screen, and remaining fine particles with coarse particles had passed through the discharge end. So, higher efficiency was obtained for screening coal at lower angle conditions.

At medium angle conditions for screening coal, more particle time on the screen has caused good mixing of the particles. But, the angle variation in the upward slope has caused reduced particle movement through the screen's discharge. This caused some of the fine and coarse particles to revolve at the center of the screen. As the particle revolution has increased, some of the fine particles that can pass through the screen have not passed, reducing efficiency for coal screening at a medium angle. At higher angle conditions for screening coal, fine and coarse particle mixing and particle time on the screen were more. It was observed that the particle movement through the discharge was reduced, causing more particle revolution in the center of the screen. The particle revolution has caused a higher impact between particles on the screen, which has caused reduced efficiency of coal screening at high angle conditions.

From the optimisation results, it was also clear that the lower level and higher level angle was optimum for coal and iron ore, respectively. It was found that the coal screening at a lower level angle provided good particle mixing and particle movement on the screen. It was also found that iron ore screening at a higher level angle provided good particle mixing and particle movement on the screen.

4.7.3 Effects of frequency on screening performance

Fig. 4.24 and 4.25 show the effect of frequency on coal and iron ore screening performance in the vibrating screen. The signal-to-noise ratio (S/N ratio) selected was larger the better, which indicates that the medium frequency was yielding higher efficiency for screening coal and iron ore. At lower frequency conditions, particle vibration was reduced, which has caused more fine particles to miss more opportunities to pass through the screen. As the sample's moisture was increased, a higher optimal frequency was required to loosen the particles on the screen, which improved the particle passing through the screen.

At medium frequency conditions, all moisture and angle conditions provided enough vibrational force for the fine particles to pass through the screen. Additionally, medium frequency has provided particle loosening and particle movement through the discharge for higher moisture conditions. It was also observed that the medium frequency had provided less intense particle vibration and mixing, which has reduced the impact between the particles causing more particles to pass through the screen. Therefore, the efficiency was higher for coal and iron ore screening at medium frequency conditions. At high-frequency conditions, particle loosening was higher, which caused some fine particles to pass through the screen. But the particle vibration was very intense, which caused a higher impact between the particles. The increased intensity of particle impact has caused some particles to revolve on the screen, reducing the particles passing through the screen.

4.7.4. Confirmation test on the optimized results of Taguchi L27 technique

From the results, it was clear that the 4% moisture content (low level), 1-degree angle (low level), and 9 Hz frequency (medium level) yielded high screening efficiency of coal. From the results, it was clear that the 4% moisture content (low level), 5-degree angle (high level), and 9 Hz frequency (medium level) yielded high screening efficiency of iron ore. Table 4.4 shows the confirmation test, which was carried out with the optimized operational parameters, and the experimental response parameter was correlated with the predicted value. From Table 4.7, it was clear that the closeness in the predicted value and the experimental value indicates the relation between the operational parameters and response parameter is in good agreement.

Table 4.7 Confirmation test and predicted results of screening efficiency (%)

Screening efficiency (%)	Optimal combination of optimal operational parameters	
	Predicted	**Experimental**
Coal	84.47%	84.40%
Iron ore	94.53%	94.56%

4.8 Significant parameters using the fractional factorial method

Table 4.8 shows the fractional factorial Design of Experiments (DOE) results for screening coal and iron ore. Fig. 4.26 and 4.27 show the Pareto chart of screening coal and iron ore. From Fig. 4.26 and 4.27, it was clear that the operational parameters were arranged in the hierarchy of the model, filling in the order of moisture, angle, and frequency. The intensity of each operational parameter is indicated in the column. Fig. 4.26 and 4.27 show that the moisture has the highest column length in the Pareto chart for screening coal and iron ore compared to angle and frequency. The moisture parameter crosses the standardize effect line (red line) of fractional factorial method and full factorial method thereby showing its significance level. Fig. 4.26 and 4.27, it was clear that the moisture content is the statistically significant value compared to angle and frequency.

Fig. 4.28 and 4.29 show the normal effect plot of the forward selection fractional factorial design for separating coal and iron ore in the screening machine. The normal effect plot provides the significant operational parameters affecting the variation of the response parameter. The normal effect plot arranges the individual significant operational parameters in points around a significant line. From Fig. 4.28 and 4.29, it was clear that the normal effect plot shows moisture content as the most significant operational parameter for separating coal and iron ore in the screening machine. The normal effect plot also validates and correlates well with the results of the Pareto chart.

Table 4.8 Fractional factorial Design of Experiments (DOE) results for screening coal and iron ore

Moisture Content (%)	Angle (degree)	Frequency (Hz)	Efficiency of coal (%)	Efficiency of iron ore (%)
4	1	12	80.45	82.84
8	1	6	59.42	76.55
4	5	6	64.87	86.21
8	5	12	54.76	69.27

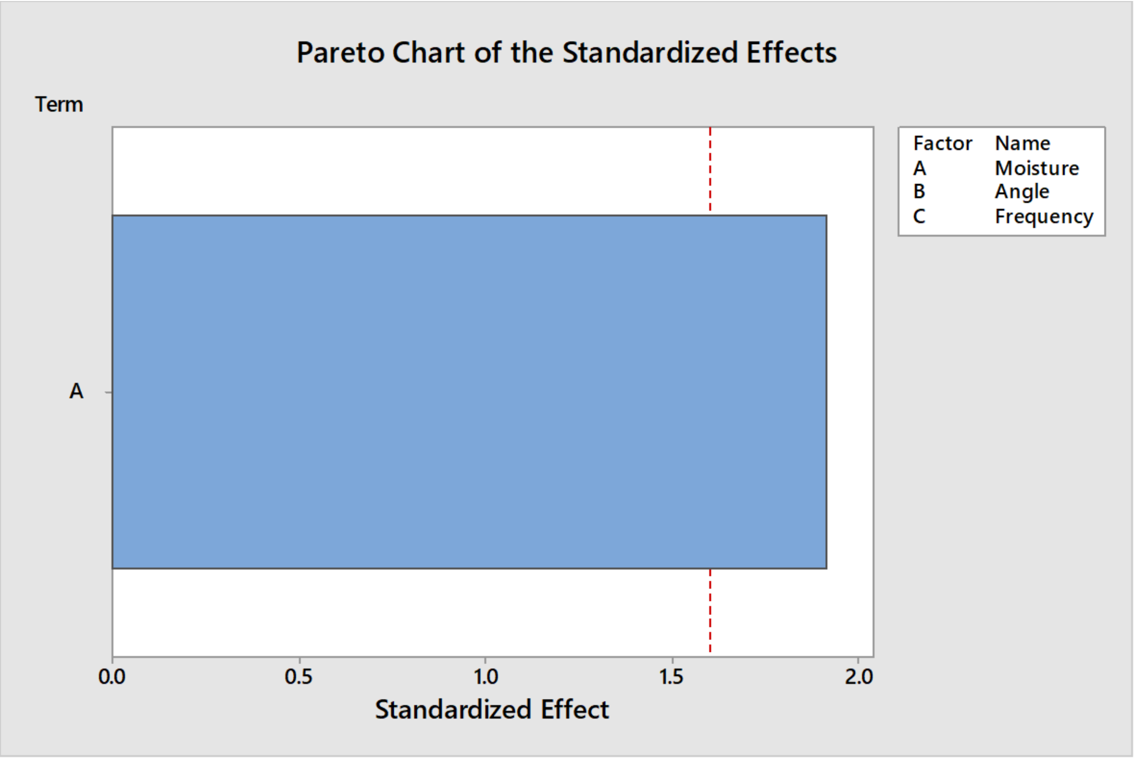


Fig. 4.26 Pareto chart for screening coal using fractional factorial design

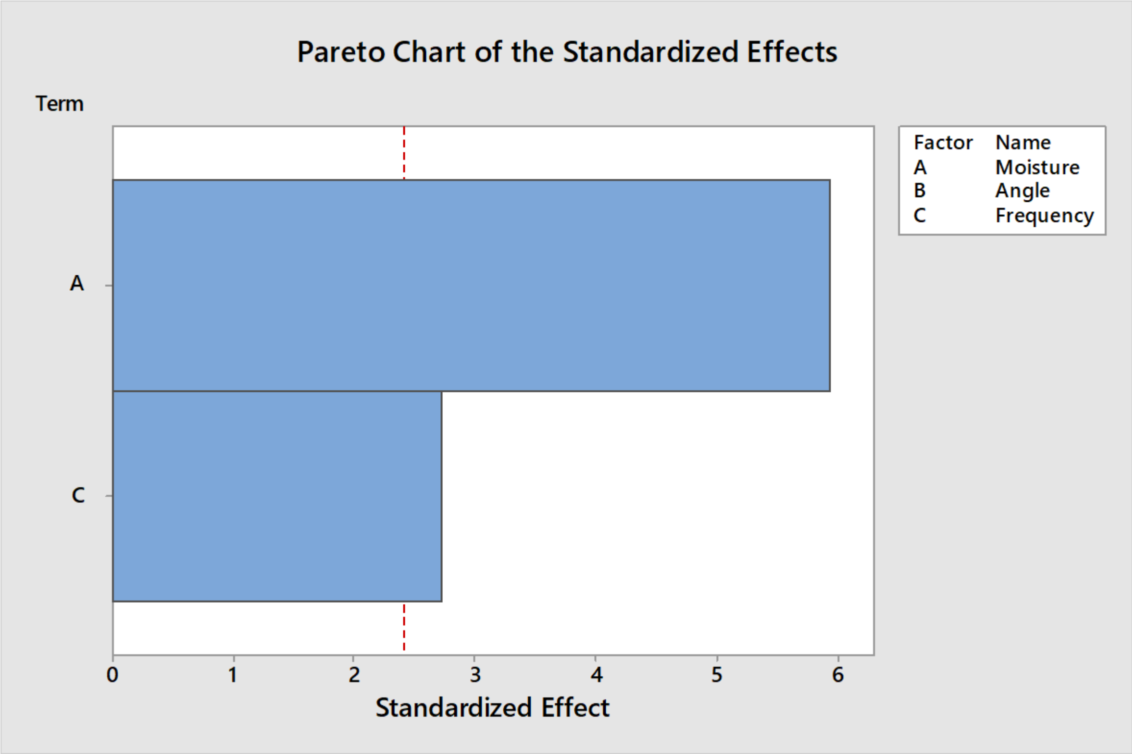


Fig. 4.27 Pareto chart for screening iron ore using fractional factorial design

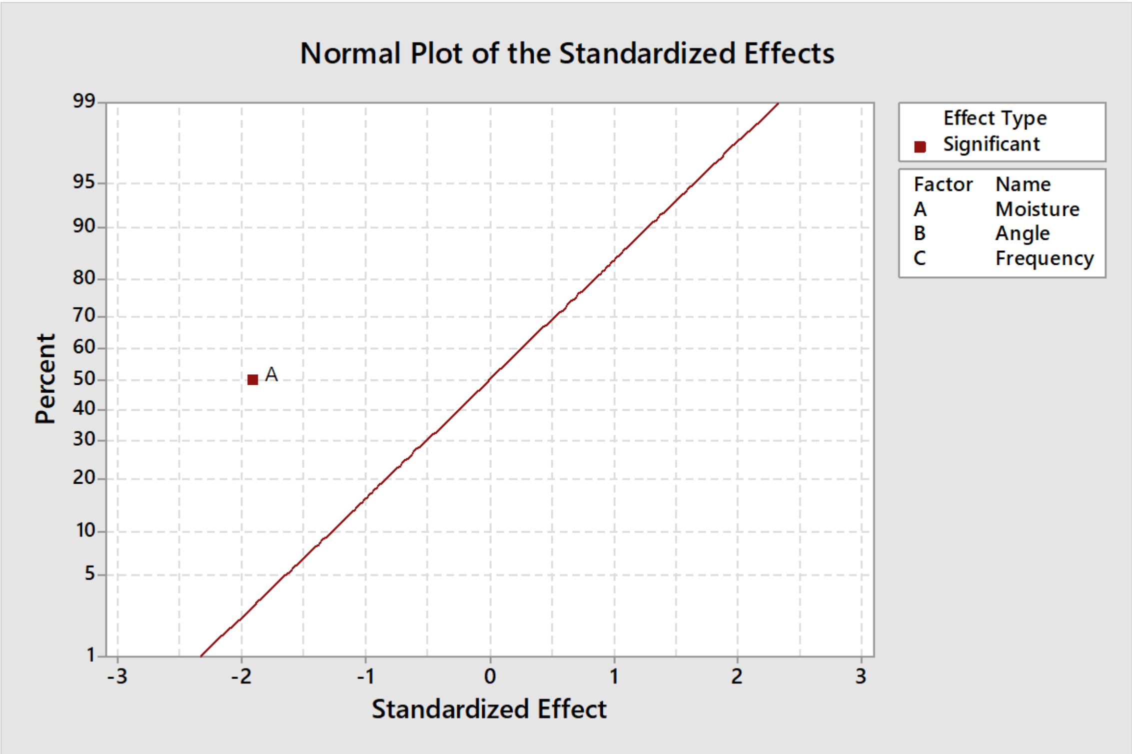


Fig. 4.28 Normal plot for screening coal using fractional factorial design

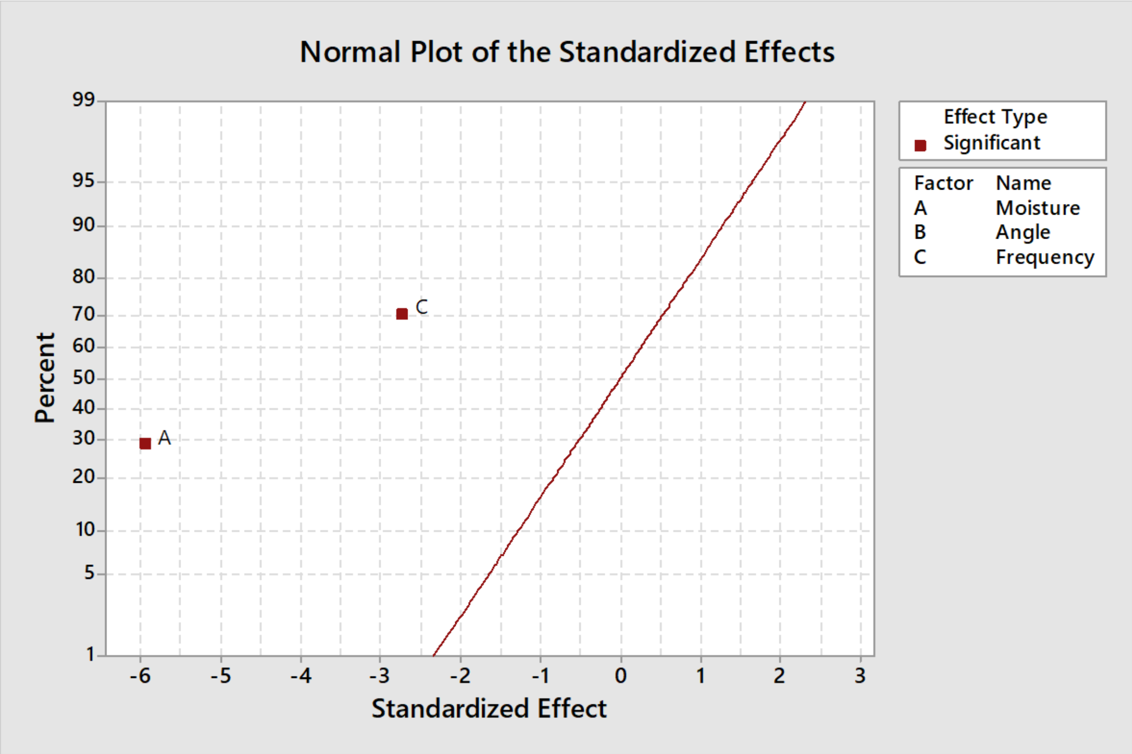


Fig. 4.29 Normal plot for screening iron ore using fractional factorial design

From the results, it was also clear that the moisture content causes the clinging of undersized particles with the oversize particles and generates near-size particles. These near-size particles attach to the screen, which causes screen blinding; thereby, moisture controls the separation efficiency of coal in the screening machine. It was also seen that the angle and frequency were less significant operational parameters compared to moisture content for screening coal. It was observed that there is a slight influence of less significant parameters such as angle and frequency affecting the screening machine's performance. The higher angle separation has reduced material movement on the screen, which has caused lesser screen exposure, thereby reducing separation efficiency.

The lower frequency separation has reduced particle stratification on the screen deck, which has reduced separation efficiency. For screening iron ore, it was found that the frequency was the significant parameter compared to angle. This was due to the good particle movement, and higher penetration of iron ore particles has occurred at a higher frequency than coal. The results showed that the fractional design is a simpler design that combines all the operational parameters for a sequential experimental run with minimum resource utilisation.

4.9 Feeding performance of coal and iron ore

Fig. 4.29 shows the final assembly of the flexible screening machine as a feeder. The transformation of the developed screening machine to a feeding machine was carried out by replacing the screen mesh with a thin solid plate. Fig. 4.31 shows the feeding performance of coal and iron ore. From the results, it was clear that the movement of the particle was good for high-density material such as iron ore than low-density coal material. It was observed that the centrifugal force applied by the circular motion of the developed machine throws the iron ore particles farthest than the coal particles. This has caused the higher iron ore particles movement from feed end to discharge end in lesser time than coal. So, the developed screening machine can be utilised as the feeding machine with slight modification. Results showed that the developed machine could be utilised as a multifunctional machine for efficient screening with less clogging and also for efficient feeding.

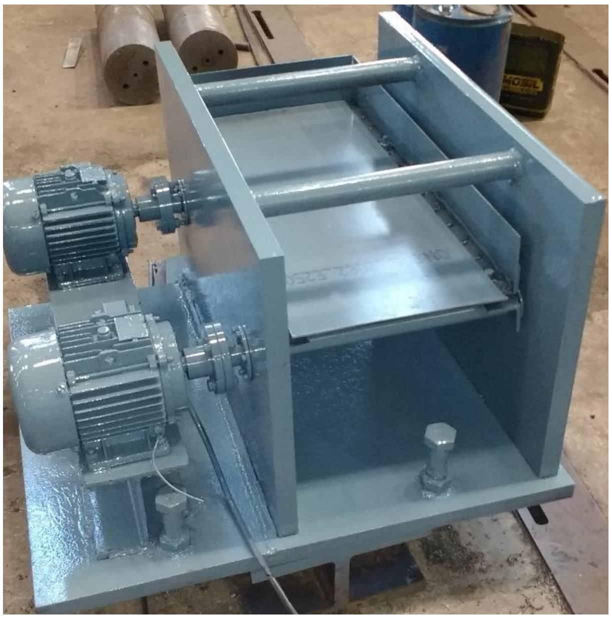


Fig. 4.30 Final assembly of the flexible screening machine as a feeder

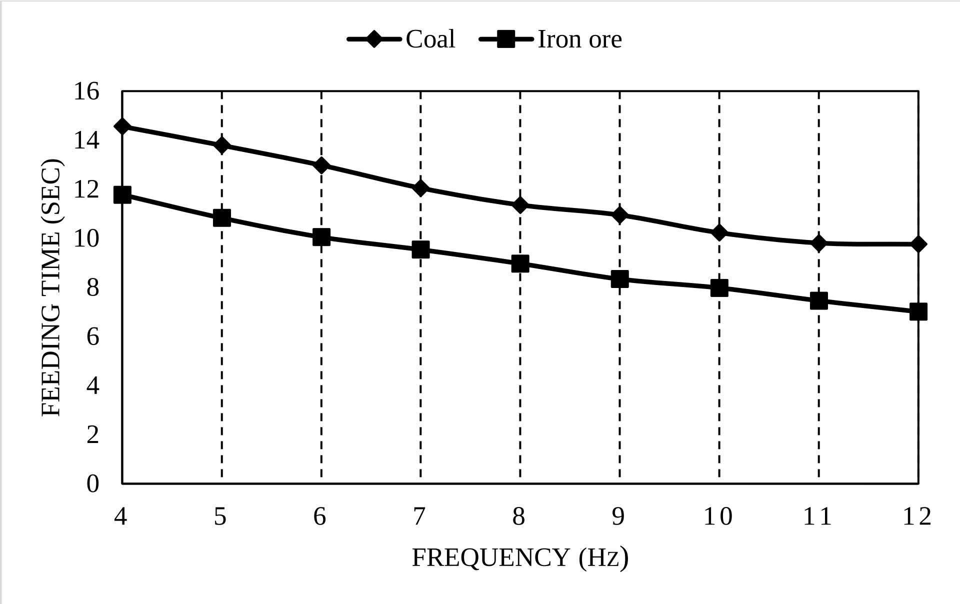


Fig. 4.31 Feeding performance of coal and iron ore

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusions

a. The flexible screening machine is designed and developed on a laboratory scale with the features of higher screening efficiency and multifunctional (Screening and feeding with minor modification)

b. Experimental evaluation of the vibratory screening machine by screening coal and iron ore for different moisture conditions gives the highest efficiency of 85.96%, 75.64%, and 63.46%, with 4%, 6%, and 8% moisture content, respectively, for coal and the highest efficiency of 94.66%, 90.45%, and 83.91% with 4%, 6%, and 8% moisture content, respectively for iron ore. This is due to the higher adhesiveness and agglomeration of coal, which has caused higher screen blinding, thereby reducing its screening efficiency.

c. The particles passing through the screen were higher for iron ore at an angular position of 3˚ and 5˚, which was due to the higher residence time and efficient particle movement from the feed end to the discharge end. For coal, the particles passing through the screen were reduced at a higher angular position which was due to inefficient particle movement from the feed end to the discharge end and higher particles rolling near the feed end.

d. Prediction results of screening efficiency using the backpropagation artificial neural network (ANN) have provided a higher R-squared value, i.e., more than 99% for the screening of coal and iron ore, than second-order polynomial regression modeling, which has given an R-squared value of more than 78.7%. A higher R-squared value indicates a higher correlation between prediction results and experimental results. The validation analysis with a normal probability plot and a histogram correlates well with the prediction results.

e. The Taguchi L27 Design of Experiments optimisation analysis showed that at 4% moisture content, 1˚ angle, and 9 Hz frequency, yield higher screening efficiency of 84.40% for coal. For iron ore, at 4% moisture content, 5˚ angle, and 9 Hz frequency yields higher screening efficiency of 94.53%. The optimized prediction results correlate well with the experimental results. The fractional Design of Experiments with a Pareto chart and normal plot showed that moisture was the most significant parameter for screening coal and iron ore. This was due to the increase in the moisture content, which has increased screen blinding which has higher control in varying the screening efficiency of the screening machine.

f. The feeding performance of coal and iron ore was analysed by replacing screen mesh with a thin solid plate. The experimental analysis showed that the feeding time of high-density material such as iron ore was lower than low-density coal material. Results also show that the developed machine can be utilised as a multifunctional machine for efficient screening with less clogging and also for efficient feeding.

g. The significant contribution of the present research work is developing a flexible screening machine with the features of lower screening blinding, low power consumption, highly efficient screening and feeding machine. Further the effects of parameters such as moisture, angle and frequency were investigated using experimental and statistical analysis. The statistical analysis such as Regression and ANN modelling has provided the accurate mathematical model for the experimental results of screening coal and iron ore. The statistical analysis such as Taguchi L27 and factorial analysis has provided the significance of each parameter effecting the performance of coal and iron ore screening using flexible screening machine.

5.2 Recommendations for Future Work

1. Experimental investigations can be carried out with different types of material to evaluate the performance of developed flexible screening machine.
2. The data analysis can be carried out using unsupervised machine learning prediction models.
3. The flexible screening machine can be modified into a double-deck screening machine.

4. The flexible screening machine can be modified to incorporate the variation of the amplitude of the screening machine, which changes the efficiency of the machine.
5. The automation of a flexible screening machine can be provided with a microcontroller and sensors, which automatically control the machine with lesser human intervention.

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Zhovtiuk, G. V., (1988). "Wet sizing of coals on stationary screens." *Coal Prep.,* 5 (3-4), 229-241.

LIST OF PUBLICATIONS BASED ON Ph.D. RESEARCH WORK

Journal

1. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H (2023), "Evaluation of the Parametric Effects of Separation of Coal in Vibration Separator Using Plackett–Burman Design of Experiments." Transactions of the Indian Institute of Metals, 1243–1252. https://doi.org/10.1007/s12666-022-02842-9
   (SCIE, Scopus) (Springer, Impact factor – 1.391)
2. Shanmugam, B.K., Vardhan, H., Raj, M.G., Kaza, M., Harish, H., Byrareddy. R. R., Sah, R., 2023, "Experimental analysis of vibratory screener efficiency based on density variation for screening coal and iron ore" International Journal of Coal Preparation and Utilisation, Article in press. 10.1080/19392699.2022.2051700
   (SCIE, Scopus) (Springer, Impact factor – 2.791)
3. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2023, "Comparison of the prediction performance of separating coal in separation equipment using cubic regression modelling and cascade neural network modelling" International Journal of Coal Preparation and Utilisation, 43:2, 248-263. 10.1080/19392699.2022.2040492
   (SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)
4. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2022, "Comparison of the predictive model performance of Taguchi's L27 and Box Behnken design optimisation method for separating coal in vibrating screen" International Journal of Coal Preparation and Utilisation, 43:3, 436-447. 10.1080/19392699.2022.2051700
   (SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)
5. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2021, "Application of fractional factorial design for evaluating the separation performance of the screening machine" International Journal of Coal Preparation and Utilisation, 42:11, 3369-3379. 10.1080/19392699.2021.1962312
   (SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)

6. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2021, “Investigation on the operational parameters of screening coal in the vibrating screen using Taguchi L27 technique.” International Journal of Coal Preparation and Utilisation, 42:11, 3282-3291. 10.1080/19392699.2021.1957854
(SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)
7. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2019, “ANN modeling and residual analysis on screening efficiency of coal in vibrating screen” International Journal of Coal Preparation and Utilisation, 42:10, 2880-2894. 10.1080/19392699.2021.1910505
(SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)
8. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2021, “Artificial neural network modeling for predicting the screening efficiency of coal with varying moisture content in the vibrating screen” International Journal of Coal Preparation and Utilisation, 42:6, 2656-2674. 10.1080/19392699.2021.1871610
(SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)
9. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2021, “Regression modelling and residual analysis of screening coal in vibrating screen” International Journal of Coal Preparation and Utilisation, 42:9, 2849-2864. 10.1080/19392699.2021.1923488
(SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)
10. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2020, “Experimentation and statistical prediction of screening performance of coal with different moisture content in the vibrating screen” International Journal of Coal Preparation and Utilisation, 42:6, 1804-181. 10.1080/19392699.2020.1767606
(SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)
11. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2019, “Screening performance of coal of different size fractions with variation in design and operational flexibilities of the new screening machine”

Energy Sources, Part A: Recovery, Utilisation, and Environmental Effects, 45:2, 4361-4369. 10.1080/15567036.2019.1670291
(SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)

12. Shanmugam, B.K., Vardhan, H., Govinda Raj, M. Kaza, M., Sah, R., Harish, H., 2019, "Evaluation of a new vibrating screen for dry screening fine coal with different moisture contents" International Journal of Coal Preparation and Utilisation, 42:3,752-761. 10.1080/19392699.2019.1652170
(SCIE, Scopus) (Taylor & Francis, Impact factor – 2.791)

Conference

S. No	Title	Authors and Co-authors	Journal, and Year of publication
1.	Shortcomings of vibrating screen and corrective measures: A review.	**Bharath Kumar S**, Harsha Vardhan, Govinda Raj M, Marutiram Kaza, Rameshwar Sah, & Harish H	International Conference on Emerging Trends in Engineering (ICETE) 2 (43):345–51 (2019) (Springer)
2.	The Screening Efficiency of Linear Vibrating Screen - An Experimental Investigation	**Bharath Kumar S**, Harsha Vardhan, Govinda Raj M, Marutiram Kaza, Rameshwar Sah, & Harish H	AIP Conference Proceedings 2204, 040002 (2020); (Scopus)
3.	Experimental and Prediction Analysis of the Screening Performance of Coal in Linear and Circular Vibratory Screen	**Bharath Kumar S**, Harsha Vardhan, Govinda Raj M, & Harish H	Journal of The Institution of Engineers (India) (2021)

PATENT BASED ON Ph.D. RESEARCH WORK

S. No	Title	Inventor(s)	Patent No.	Date and Country
1	Material handling system for screening or feeding materials with high screening efficiency and energy efficiency	**Mr. Shanmugam Bharath Kumar**, Dr. Maruthiram Kaza, Dr. Harsha Vardhan, Dr. Govinda Raj Mandela, Dr. Rameshwar Sah, Dr. Arindam Roy Choudary, Mr. Naveena Omkarappa, Mr. Nagaraju Venkategouda	Patent application number - TEMP/E-1/53448/2018-MUM Application No. 201821048990	24-12-2018 (Patent filed) 26-06-2020 (Patent published) (India)

Award

- Received **"Best Paper Award"** from 35th Indian Engineering Congress organized by The Institution of Engineers (India) for the paper "Experimental and Prediction Analysis of the Screening Performance of Coal in Linear and Circular Vibratory Screen" for the year 2020 published in the Journal of The Institution of Engineers (India).

BIODATA

Personal Information

Name	Bharath Kumar S					
Date of Birth	02-09-1989	Gender	Male			
Permanent Address	Door no, 886/13A, 3rd cross, Sewage farm road, Vidyaranyapuram, Mysuru, Karnataka- 570008					
Temporary Address	House number-36, 12th Main road, Puttaiah road, Vrushabavathi nagar, Kamakshipalya, Bengaluru- 079					
Email ID	shanmugabharathkumar@gmail.com					
Mobile no.	8095795794	Alternate Mob. No.	8431585946			
Nationality	Indian	Religion	Hindu	Category	OBC	
Blood Group	B+ve	Height (in cms.)	168	Weight (in kgs.)	98	

Languages known	Language	Speak	Read	Write
	Kannada	Yes	Yes	Yes
	English	Yes	Yes	Yes
	Hindi	Yes	Yes	Yes
	Telugu	Yes	Yes	
	Tamil	Yes		

Education Details *(starting from the highest degree)*

Qualification	Year of Passing	Board / University	Percentage/CGPA Scored
Ph.D	2023	National Institute of Technology Karnataka, Surathkal	9.25
M. Tech	2014	P.E.S College of Engineering, Mandya, Karnataka	9.14

B. E	2011	P.E.S College of Engineering, Mandya, Karnataka	68.58

Profile professional career/life sketch

I belong to a middle-class family. I was born in Mysuru, Karnataka. I did my B.E. in Mechanical Engineering and M.Tech in Computer Integrated Manufacturing (Automation and Robotics) from P.E.S College of Engineering, Mandya, Karnataka. I have 3 years of experience as Assistant Professor in Department of Mechanical Engineering from Srinivas Institute of Technology, Mangalore. I did my Ph.D in National Institute of Technology Karnataka, Surathkal from July 2017. I have published 19 SCI papers, 6 Scopus papers, and 3 patents (1 Granted and 2 Published).

I don't want to elaborate on my professional career anymore as the total details are given in this application. I am a silent worker and believe in hard work. I love nature a lot. I got married in 2018 to Shobha Rani K.

My Ph.D. topic entitled "**Design and development of flexible screen for processing industries and its performance prediction using machine learning techniques**" is the collaborative work carried out with NITK Surathkal, India and JSW Steel Ltd., Ballari, India

Area of Research Activity

1. **Material Processing**
2. **Machine Learning**
3. **Natural Fiber Composites**
4. **Conceptual Design**
5. **Agricultural Machineries**

Summary of Publications

Sl.no	Publications	Numbers
1.	Papers published in journals	22: International Journals (19: SCI, 3: Scopus)
2.	Papers published in conferences / seminars	3 (Scopus)
3.	Patents	1 Granted and 2 Published
4.	Awards	1 Best paper awards
5.	Total citations	260 (Scopus) H-index -12 (Scopus ID - 57210463940) 300 (Google scholar) H-index -13

Research Publications: *(SCIE)*							
List of Publications in Journals							
Sl. No.	Title of the Publication	Authors	Journal Name	Volume	Page No.	Year of Publication	Impact Factor
1.	Experimental analysis of vibratory screener efficiency based on density variation for screening coal and iron ore	**Bharath Kumar Shanmugam,** Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	International Journal of Coal Preparation and Utilization, Taylor & Francis	Article in press		2023	2.791 (SCIE)
2.	Influence of Microstructural Characteristics on Wear and Corrosion Behaviour of Si3N4-Reinforced Al2219 Composites	C. J. Manjunatha, C. Durga Prasad, Harish Hanumanthappa, A. Rajesh Kannan, Dhanesh G. Mohan, **Bharath Kumar Shanmugam**, C. Venkategowda	Advances in Materials Science and Engineering, Hindawi	Article in press		2023	2.098 (SCIE)
3.	Evaluation of the Parametric Effects of Separation of Coal in Vibration Separator	**Bharath Kumar Shanmugam,** Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah	Transactions of the Indian Institute of Metals, Springer	76	1243–1252	2023	1.391 (SCIE)

	Using Plackett–Burman Design of Experiments	& Harish Hanumanthappa					
4.	**Comparison of the predictive model performance of Taguchi's L27 and Box Behnken design optimization method for separating coal in vibrating screen**	**Bharath Kumar Shanmugam,** Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	**International Journal of Coal Preparation and Utilization, Taylor & Francis**	**43: 3**	**436-447**	**2023**	**2.791 (SCIE)**
5.	**Screening performance of coal of different size fractions with variation in design and operational flexibilities of the new screening machine**	**Bharath Kumar Shanmugam,** Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	**Energy Sources, Part A: Recovery, Utilization, and Environmental Effect, Taylor & Francis**	**45: 2**	**4361-4369**	**2023**	**2.902 (SCIE)**
6.	**Computational modelling for the manufacturing of solar-powered multifunctional agricultural robot**	Mohan Poojari, Harish Hanumanthappa, C Durga Prasad, Harshitha Madhusoodan Jathanna, Ananth Raj Ksheerasagar,	**International Journal on Interactive Design and Manufacturing (IJIDeM), Springer**	**Article in press**		**2023**	**2.639 (SCIE)**

		Prathiksha Shetty, **Bharath Kumar Shanmugam**, Hitesh Vasudev					
7.	**Comparison of the prediction performance of separating coal in separation equipment using machine learning based cubic regression modelling and cascade neural network modelling**	**Bharath Kumar Shanmugam,** Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	**International Journal of Coal Preparation and Utilization, Taylor & Francis**	**43: 2**	**248-263**	**2023**	**2.791 (SCIE)**
8.	**High-Temperature Tribological Studies on Hot-Forged Al6061–TiB2 In Situ Composites**	C Venkategowda, Harish Hanumanthappa, C Durga Prasad, **Bharath Kumar Shanmugam**, TN Sreenivasa, MS Rajendra Kumar	**Journal of Bio-and Tribo-Corrosion, Springer**	**8**	**101**	**2022**	**3.311 (SCIE)**
9.	**Numerical approach for optimization of magnetic roller and evaluating the performance of permanent magnet roller separator**	GT Mohanraj, Sharnappa Joladarashi, Harish Hanumanthappa, **Bharath Kumar Shanmugam**, Harsha Vardhan,	**Alexandria Engineering Journal, Elsevier**	**61: 12**	**13011 - 13033**	**2022**	**6.626 (SCIE)**

	through design of experiment	Gajanan M Naik, P Devadas Bhat, MR Rahman					
10	**Experimental and Statistical Evaluation of the Mechanical Performance of (Jute and Cocopeat) Plant and (Silk) Animal-based Hybrid Fibers Reinforced with Epoxy Polymers**	Lokesh Kanchugaranahally Sriramamurthy, **Bharath Kumar Shanmugam Nagarathna**, Thandra Paavan Kumar, Harish Hanumanthappa, Mohanraj Thimmegowda, Shrinivasa D Mayya, Shobharani Krishnameena Yashaswini Srivatsav, Aishwarya Brindha Kavitha Kumar	**Journal of Natural Fibers, Taylor & Francis**	**19: 16**	**12664 - 12675**	**2022**	**3.507 (SCIE)**
11	**Application of fractional factorial design for evaluating the separation performance of the screening machine**	**Bharath Kumar Shanmugam**, Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	**International Journal of Coal Preparation and Utilization**	**42: 11**	**3369-3379**	**2022**	**2.791 (SCIE)**
12	**Investigation on the operational parameters of screening coal**	**Bharath Kumar Shanmugam**, Harsha Vardhan, M. Govinda Raj,	**International Journal of Coal Preparatio**	**42: 11**	**3282-3291**	**2022**	**2.791 (SCIE)**

	in the vibrating screen using Taguchi L27 technique	Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	**n and Utilization**				
13	**Experimentation and prediction analysis on the mechanical performance of fish scale and coconut shell powder-based composites**	KS Lokesh, **Bharath Kumar Shanmugam**, Shrinivasa D Mayya, BP Panduranga, Naveen JR Kumar, Harish Hanumanthappa	**Journal of Natural Fibers, Taylor & Francis**	**19: 14**	**7750-7761**	**2022**	**3.507 (SCIE)**
14	**ANN modeling and residual analysis on screening efficiency of coal in vibrating screen**	**Bharath Kumar Shanmugam**, Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	**International Journal of Coal Preparation and Utilization**	**42: 10**	**2880-2894**	**2022**	**2.791 (SCIE)**
15	**Regression modeling and residual analysis of screening coal in screening machine**	**Bharath Kumar Shanmugam**, Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	**International Journal of Coal Preparation and Utilization**	**42: 9**	**2849-2864**	**2022**	**2.791 (SCIE)**

16	Artificial neural network modeling for predicting the screening efficiency of coal with varying moisture content in the vibrating screen	**Bharath Kumar Shanmugam**, Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	International Journal of Coal Preparation and Utilization	42: 6	2656-2674	2022	2.791 (SCIE)
17	Experimentation and statistical prediction of screening performance of coal with different moisture content in the vibrating screen	**Bharath Kumar Shanmugam**, Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	International Journal of Coal Preparation and Utilization	42: 6	1804-1817	2022	2.791 (SCIE)
18	Evaluation of a new vibrating screen for dry screening fine coal with different moisture contents	**Bharath Kumar Shanmugam**, Harsha Vardhan, M. Govinda Raj, Marutiram Kaza, Rameshwar Sah & Harish Hanumanthappa	International Journal of Coal Preparation and Utilization	42: 3	752-761	2022	2.791 (SCIE)
19	Design and fabrication of optimized magnetic roller for	GT Mohanraj, MR Rahman, Sharnappa Joladarashi, Harish	Advanced Powder Technology	32: 2	546-564	2021	4.969 (SCIE)

	permanent roll magnetic separator (PRMS): Finite element method magnetics (FEMM) approach	Hanumanthappa, **Bharath Kumar Shanmugam**, Harsha Vardhan, Shahid Azam Rabbani					
20	**Investigation on iron ore grinding based on particle size distribution and liberation**	Harish Hanumanthappa, Harsha Vardhan, Govinda Raj Mandela, Marutiram Kaza, Rameshwar Sah, **Bharath Kumar Shanmugam**, Suribabu Pandiri	**Transactions of the Indian Institute of Metals, Springer**	**73**	**1853-1866**	**2020**	**1.391 (SCIE)**
21	**Estimation of grinding time for desired particle size distribution and for hematite liberation based on ore retention time in the mill**	Harish Hanumanthappa, Harsha Vardhan, Govinda Raj Mandela, Marutiram Kaza, Rameshwar Sah, **Bharath Kumar Shanmugam**	**Mining, Metallurgy & Exploration, Springer**	**37**	**481-492**	**2020**	**1.71 (SCIE)**
22	**A comparative study on a newly designed ball mill and the conventional**	Harish Hanumanthappa, Harsha Vardhan, Govinda Raj Mandela,	**Minerals Engineering**	**145**	**106091**	**2020**	**5.479 (SCIE)**

	ball mill performance with respect to the particle size distribution and recirculating load at the discharge end	Marutiram Kaza, Rameshwar Sah, **Bharath Kumar Shanmugam**					
23	**Comparison of the Experimental and Modelling Results of Mechanical Characteristics of LM6 and LM9 Alloy for Tractor Application**	Chetan C Shetteppanavar, Rohan Bhausaheb Shinde, Harish Hanumanthappa, GT Mohanraj, **Bharath Kumar Shanmugam** Sudarshan, Shobharani Krishnameena Yashaswini Srivatsav, Aishwarya RathnaBrindha Kavitha Kumar	**Journal of The Institution of Engineers (India): Series D, Springer**	**104**	**99–106**	**2023**	**0.257 (Scopus)**
Research Publications: *(Scopus)*							
24	**Evaluation of the Wear Behaviour of Thermally Aged E Glass Reinforced Epoxy Composite Filled with Wollastonite Using Taguchi**	KS Lokesh, Thomas Pinto, D Shrinivasa Mayya, **Bharath Kumar Shanmugam**, BP Panduranga, Harish Hanumanthappa, GT Mohanraj	**Journal of The Institution of Engineers (India): Series D, Springer**	**103**	**505–512**	**2022**	**0.257 (Scopus)**

	L27 Technique						
25	**Effect of Wollastonite Filler on the Experimental and Microstructural Analysis of Epoxy Composite Reinforced with E-glass Fibre**	KS Lokesh, Thomas Pinto, D Shrinivasa Mayya, **Bharath Kumar Shanmugam**, BP Panduranga, Harish Hanumanthappa, GT Mohanraj	**Journal of The Institution of Engineers (India): Series D, Springer**	**103**	**489–496**	**2022**	**0.257 (Scopus)**
Research Publications: (Conference)							
26	The screening efficiency of linear vibrating screen-An experimental investigation	**S Bharath Kumar**, Harsha Vardhan, M Govinda Raj, Marutiram Kaza, Rameshwar Sah, H Harish	AIP Conference Proceedings	2204:1	040002	2020	Scopus (Conference)
27	Investigation of iron ores based on the bond grindability test	Harish H, Harsha Vardhan, M Govinda Raj, Marutiram Kaza, Rameshwar Sah, Abhishek Sinha, **S Bharath Kumar**	AIP Conference Proceedings	2204:1	040006	2020	Scopus (Conference)
28	Machine vision for tool status monitoring in turning Inconel 718	YD Chethan, HV Ravindra, **S Bharath Kumar**	Materials Today: Proceedings	2:4–5	1841-1848	2015	Scopus (Conference)

	using blob analysis						

Conferences/Seminars/Workshops					
Sl. No.	Name of the Event	National/ International	Date	Name of the Organizer	Credits Earned
1	Emerging Research in Civil, Aeronautical and Mechanical Engineering (ERCAM-2019)	International	July 25-26, 2019	Nitte Meenakshi Institute of Technology Bangalore, India	
2	35 Indian Engineering Congress	International	December 18th - 20th, 2020	The Institution of Engineers (India)	Best Paper Award

Experience Details *(please specify number of years in each field)*			
Teaching	Research	Others (Industry)	Total
3.6 Years	5 Years	10 Months	8.6 Years

Employment History *(Starting from current employment)*			
Name of the Organization	Date of Joining	Date of Relieving	Position Held
RNS Institute of Technology, Bengaluru	06-10-2023	Still working	Assistant Professor
JSW Steel Limited, Bellary	12-02-2018	15-12-2018	Research scholar
National Institute of Technology Karnataka, Surathkal	10-07-2017	08-07-2022	Full time research scholar with teaching assistance

Srinivas Institute of Technology, Mangaluru	27-07-2014	01-07-2017	Assistant Professor

Awards & Citations received during professional career

1. Received "Poster Presentation" from Society of Mining Engineers (SME) conference organized by NITK, Surathkal for the paper "Influence of crushed raw materials and crushed- sieved raw materials on grindability to obtain required product particle size distribution" for the year 2020.
2. Received "Best Paper Award" from 35 Indian Engineering Congress organized by The Institution of Engineers (India) for the paper "Experimental and Prediction Analysis of the Screening Performance of Coal in Linear and Circular Vibratory Screen" for the year 2020 published in the Journal of The Institution of Engineers (India).

Certification courses

1. Completed certification course on "Machine Learning" offered by Stanford University (Coursera).

Achievements

1. Received a Research fellow scholarship from MHRD during Ph.D.
2. Ph.D. project work was carried out with the collaboration of NITK, Surathkal, and JSW Steel Limited, Bellary.
3. Received scholarship under TEQIP during M.Tech.
4. Received second rank in M.Tech.
5. Represented college for Shotput event in Visvesvaraya Technological University sports.
6. Won Prizes in events like shotput, discus throw, and games like Throw ball, Kabaddi at the high school and college level.

Declaration:

I, Bharath Kumar S., hereby declare that all the information I provided in this Biodata is true to the best of my knowledge.

Date: 06/09/2023

Bharath Kumar

Place: Mysuru, Karnataka

Signature